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MORPHOLOGY AND VARIABILITY OF THE CUCURBIT BLACK ROT FUNGUS [1]

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INTRODUCTION

The cucurbit black rot fungus was first described by Fautrey and Roumeguère (*17*) [3] on a Chinese variety of cucumber in France in 1891 and designated as *Ascochyta cucumis*. A little later in the same year Passerini (*18*) described the fungus *Didymella melonis* on *Cucumis melo* L. in northern Italy without knowledge of its association with *Ascochyta*, while Chester (*2*) described the same fungus on *Citrullus vulgaris* Schrad. in Delaware under the name *Phyllosticta citrullina* without recognizing the ascigerous stage. After further study in Delaware, C. O. Smith (*19*) (1905) named it *Ascochyta citrullina*. When he discovered the ascigerous stage, he described it as *Sphaerella citrullina*. Grossenbacher (*4*) designated the imperfect stage of the fungus a member of the genus *Diplodina*, and referred the ascigerous stage to the genus *Mycosphaerella*. Potebnia (*14*) reported a fungus on *Cucumis melo* L. under the name *Ascochyta melonis* which was considered to be closely associated with *Didymella melonis* Pass. He was of the opinion that *A. citrullina* (Chester) C. O. Sm. on watermelon was a form intermediate between *A. cucumis* Fautr. and Roum. and *A. melonis* Poteb. As a result of further studies on Fautrey's collection, Keissler (*10*) considered the three names to be synonyms, and recognized *Ascochyta cucumis* Fautr. and Roum. as the first valid name for the imperfect stage. It is interesting to note that Ferraris (*3*) published a species on *Cucumis melo* L. in the northern part of Italy under the name of *Sphaerella melonis* and claimed that the asci are nonparaphysate. The description of Ferraris' *Sphaerella melonis* showed that it is the same fungus as Passerini's *Didymella melonis* and of C. O. Smith's *Sphaerella citrullina*. There is no specific difference between either one of the European forms and the American fungus.

The pleomorphism and variability of this fungus were the cause of some of the confusion in its early classification of the imperfect stage. Chester (*2*) described it as *Phyllosticta citrullina* on account of its continuous spores, while Keissler (*10*), in studying Fautrey's collection on *Cucumis melo* L., failed to recognize the micropycnospore

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[3] Italic numbers in parentheses refer to Literature Cited, p. 101.

stage as a phase of the fungus, and thought it to be *Phyllosticta orbicularis* Ell. and Ev. More recently, Wiant (*24*) pointed out that there is considerable variation in the size of pycnidia and perithecia and in the relative abundance of nonseptate spores. He also observed that the extent of sporulation varied in different isolates.

The present study is concerned with the variability of the morphology and cultural characters of the cucurbit black rot fungus. It is shown that the proper binomial of the fungus is *Mycosphaerella cucumis* (Fautr. and Roum.) nov. comb.

EXPERIMENTAL RESULTS

SOURCE AND CHARACTERISTICS OF CULTURES

The black rot disease was found to be endemic in a watermelon-growing area near Merrimac, Wis. Vines of the Hawkesbury variety of watermelon were collected on August 27, 1945, and from these tissue-fragment cultures were made. On September 13, 1945, specimens containing both pycnidia and perithecia were obtained from the same source. Single-spore cultures from ascoespores and from pycnospores were made. The isolates from pycnospores were of two types. One type sporulated very sparsely; the other produced pycnidia promptly and abundantly. The first type was designated as *A* and the second type as *As*.

Successive transfers of the aerial mycelium of *As* isolates resulted in cultures similar to *A*. On the other hand, *As* sectors appeared suddenly and rather frequently in *A* cultures. From mature perithecia in such sectors 54 single ascospores were picked. The colonies which resulted fell into 4 groups. About 8 percent were *As* type; about 85 percent were of a type designated as *B–a*; about 2 percent were of a type designated as *B–1a*; and 5 percent were referred to as type *B–b*. The cultural characters of the 5 types are described briefly as follows:

A.—Aerial mycelium vigorous, white, becoming gray with age; submerged mycelium dark olive to black; growth fairly rapid; usually sterile; sectors of *As* type with fruiting bodies appearing frequently.

As.—Aerial and submerged mycelium identical with that of *A*, aerial mycelium turning gray more rapidly; growth fairly rapid; abundant dark to black pycnidia, perithecia, and "pseudoperithecia."

B–a.—Aerial mycelium usually absent, very scanty when present; submerged mycelium hyaline at first, becoming dark olive to black; numerous small pycnidia, light brown at first, turning brownish black; black perithecia and "pseudoperithecia" appearing abundantly later.

B–1a.—Aerial mycelium absent or sparse; submerged mycelium hyaline at first, becoming olive green to greenish black; numerous large pycnidia produced promptly; perithecia and "pseudoperithecia" appearing late and sparsely.

B–b.—Original character intermediate between *B–a* and *As*, later changing to *As*.

The types mentioned above and certain other types described later are illustrated in figure 1.

PYCNIDIAL STAGE

There is evidence in certain species of *Mycosphaerella* that microconidia function as spermatia. The earliest record of the so-called spermagonium was made by Higgins (*6*) (1914) in *M. nigerristigma* Higgins. Klebahn (*12*) applied the name micropycnidia to the small

conidia in *M. hieracii* (Sacc. and Briosi) Jaap. Snyder (*20*) pointed out that the so-called pycnospores of *M. brassicicola* (Fr.) Lindau did not germinate under the conditions studied and suggested that they probably were spermatia. There is no evidence as yet that micropycnospores of *Mycosphaerella* having an *Ascochyta* stage function as spermatia.

Pycnidia bearing either micropycnospores or macropycnospores were present constantly in the sporulating cultures of *Mycosphaerella cucumis* studied. Production of one or both types on certain media varied with the strain of the organism. In general, pycnidia bearing microspores could be induced in *A* cultures by ultraviolet irradiation on potato-dextrose agar, while in *As* cultures they were produced

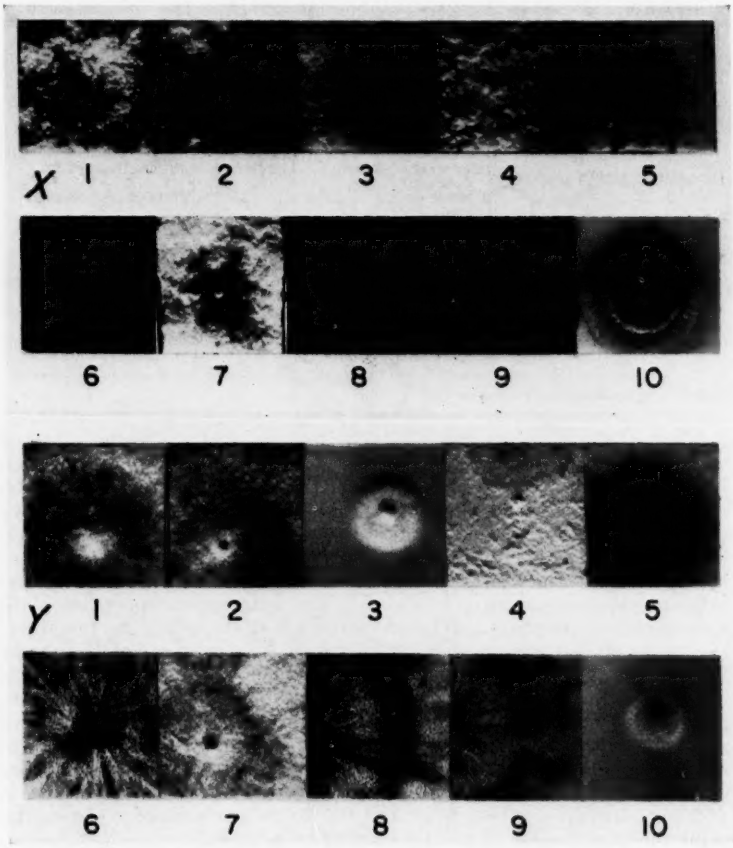

FIGURE 1.—Seven-day cultures of variants of *Mycosphaerella cucumis*. *x*, Growth on oatmeal-dextrose agar. *y*, Growth on potato-dextrose agar. The strains are indicated as follows: *1*, *As* (wild type); *2*, *A*; *3*, *A–1*; *4*, *A–2*; *5*, *A–2s*; *6*, *B–a*; *7*, *B–b*; *8*, *B–1a*; *9*, *B–1b*; *10*, *B–3*.

naturally on both potato-dextrose agar and oatmeal-dextrose agar. In *B–a* and *B–1a* cultures both types of pycnidia occurred on oatmeal-dextrose agar, but only pycnidia producing microspores occurred on squash-extract agar. On potato-dextrose agar, microspores predominated in *B–a* cultures and macrospores in *B–1a* cultures. The sizes of pycnidia and pycnospores are compared in table 1. It is evident that pycnidia varied greatly in size on culture media. The range of size of pycnidia from naturally infected watermelon stems was somewhat narrower (50 μ–150 μ). The size and shape of pycnidia from several sources are illustrated in figure 2.

TABLE 1.—*Measurements of pycnidia and pycnospores of variants of Mycosphaerella cucumis*

Measurement	Agar medium	Range and mode of size in variants indicated			
		A	*As*	*B–a*	*B–1a*
		Microns	*Microns*	*Microns*	*Microns*
Diameter of pycnidia	Potato-dextrose.	90–200 [1]	80–180	60–150	60–170.
	Oatmeal-dextrose.	60–200	80–200	60–165	85–330.
	Squash-extract.			70–160	80–180.
Width and length of micropycnospores.	Potato-dextrose.	1.5–3 × 4–8	1.5–3 × 3–9	2–4 × 4–10	
	Oatmeal-dextrose.	2–2.5 × 6–9	1.5–3 × 3–9	2–4.5 × 4–9	2.5–5 × 4–9.
	Squash-extract.			2–3 × 6–8	1.5–2.5 × 5–9.
Width and length of macropycnospores.	Potato-dextrose.				2.5–5 × 5–14.
	Oatmeal-dextrose.			5–7 × 10–13	5–5.5 × 9–1?

[1] Produced by irradiation with ultraviolet.

Most of the pycnospores obtained from naturally infected material were nonseptate, with a size range of 2.5μ–4.5μ x 5μ–10μ. Variation in septation of pycnospores of all the isolates was considerable on culture media. Pycnospores could be divided as to size into two classes, designated herein as micropycnospores and macropycnospores. The size range of the micropycnospores was quite similar in the variant types and on the different media used. Generally speaking, the micropycnospores were unicellular. The macropycnospores of *B–1a* were mostly uniseptate and occasionally biseptate, while the macropycnospores of *B–a* were mostly nonseptate. In a reisolate of *B–1a* type from overwintering watermelon stems all pycnospores were uniseptate. There was no relation between size of pycnidium and size of spore produced. Some very small pycnidia produced macropycnospores and some large pycnidia produced micropycnospores. A few microspores sometimes appeared in a pycnidium in which macrospores predominated but the reverse was not noted. The small pycnidia of *B–a* on oatmeal-dextrose agar and the larger pycnidia of *B–1a* on the same medium produced mostly macropycnospores.

The micropycnospores and macropycnospores did not appear to differ in function. They were equally germinative and developed

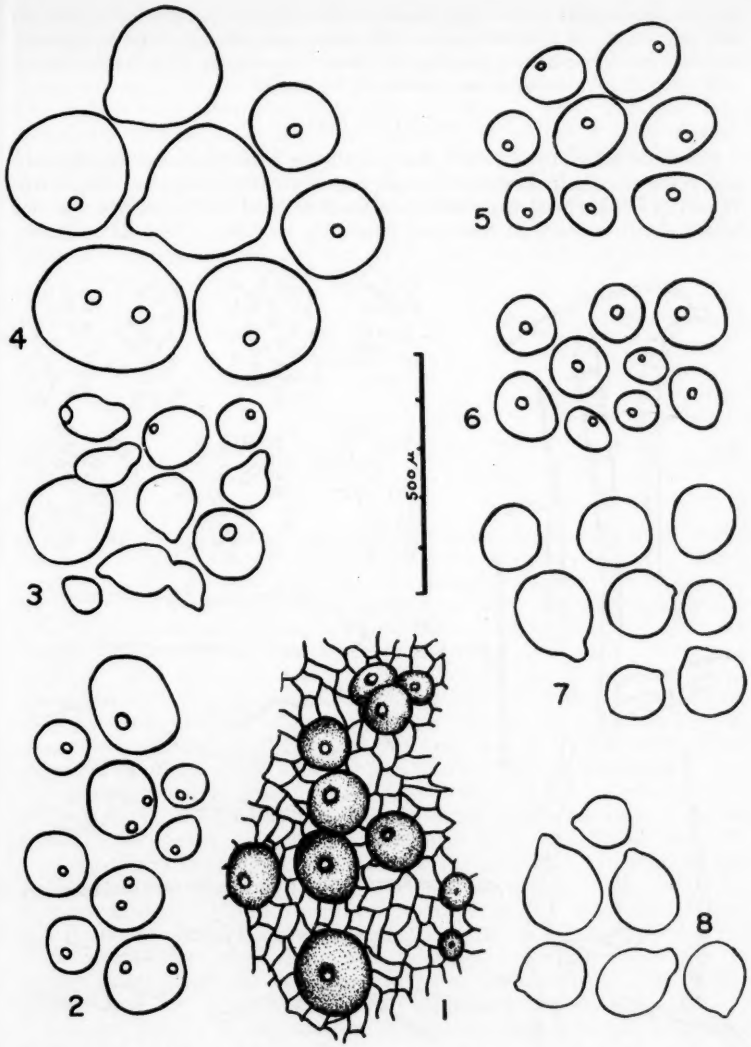

FIGURE 2.—Variation in size and shape of pycnidia. *1, As,* wild type on watermelon stem; *2, As* type on oatmeal-dextrose agar; *3, A* type on potato-dextrose agar after ultraviolet irradiation; *4, B–1a* type on oatmeal-dextrose agar; *5, B–1a* type on squash-extract agar; *6, B–a* type on squash-extract agar; *7, B–a* type on oatmeal-dextrose agar; *8,* "pseudoperithecia" of *B–a* type on oatmeal-dextrose agar.

into colonies true to the type from which they were taken if no mutation occurred. Later studies on the development of perithecia did not indicate that the micropycnospores were concerned with fertilization.

Types of pycnospores are shown in figure 3.

ASCIGEROUS STAGE

Grossenbacher (*4*) studied the perithecia from diseased muskmelon and recorded their diameter as ranging from 100μ to 165μ. Recently Wiant (*24*) observed the perithecia from several curcurbit species and found them to vary in diameter from 71μ to 224μ. The dark-brown

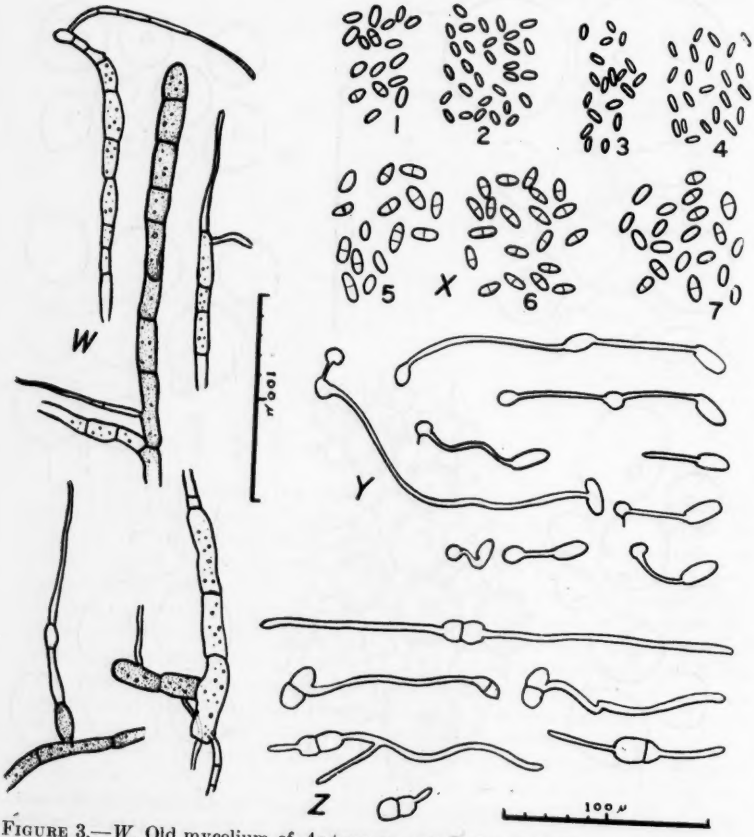

FIGURE 3.—*W*, Old mycelium of *As* type on potato-dextrose agar. *X*, Variation in size, shape, and septation of pycnospores: *1*, from naturally infected watermelon stem; *2*, *As* type on oatmeal-dextrose agar; *3*, *B–a* type on squash-extract agar; *4*, *B–1a* type on squash-extract; *5*, *B–1a* type on oatmeal-dextrose agar; *6*, *B–1a* reisolate after overwintering on watermelon stem; *7*, *B–a* type on oatmeal-dextrose agar. *Y*, Micropycnospores germinating (24 hours at 24° C.) in 2 percent orange extract. *Z*, Macropycnospores germinating (24 hours at 24° C.) in 2 percent orange extract.

to black color and the globose to inverted oval shape have been recorded in all descriptions since Grossenbacher (*4*, *13*, *24*). In the present investigation the perithecia were mostly globose to subglobose either on naturally infected watermelon stem or on culture media. The mature perithecia were dark brown to black. They were partially embedded or erumpent in the diseased tissue and on culture media. Measurements of perithecia, asci, and ascospores given in table 2 show that the perithecia were largest in *B–a* and *B–1a* cultures. The sizes of asci and ascospores were about the same in all isolates.

TABLE 2.—*Average measurements of perithecia, asci, and ascospores on watermelon and on oatmeal-dextrose agar*

Organ	From watermelon stem canker	From the isolate indicated grown on oatmeal-dextrose agar		
		As	*B-a*	*B-1a*
	Microns	*Microns*	*Microns*	*Microns*
Perithecia	90–120	75–125	78–190	70–230
Asci	6-10×56–70	8–10×55–88	6–9×65–80	8–12×55–80
Ascospores	4. 5-6×8–15	5–7×12–15	6–9×12–15	5–7. 5×11–15. 5

The fascicled asci were hyaline and each ascus contained eight bicelled fusiform ascospores either in one or in two series. Many mature perithecia were studied. No paraphyses were found among the asci. However, in young perithecia there were paraphysislike structures which were close to those illustrated by Klebahn (*13*) for *Didymella lycopersici*. Perithecia of different ages were picked and studied. It was found that in certain young perithecia such paraphysislike structures were more numerous than asci while in older ones they were less common or absent. Since the asci did not all mature at the same time and since abortion was common, these structures were regarded as immature or abortive asci and not as true paraphyses.

A peritheciumlike fruiting body was always found associated with the perithecia in agar cultures, usually being produced slightly earlier than the perithecia. Such structures were indistinguishable from the true perithecia in shape, color, and size (110μ–160μ). Instead of asci and ascospores, there were produced within, spores in chains which separated later. Spores were of one to three, mostly two cells, hyaline, nearly spherical, and 6μ×7μ to 6μ ×19μ in size. They were discharged from the fruiting body along with granular material. Since the internal structure of the fruiting body was distinct from that of the perithecium, the name pseudoperithecium was applied.

Various phases of the ascigerous and pseudoperithecial stages are illustrated in figure 4.

DEVELOPMENT OF FRUITING BODIES

The developmental history of the fruiting bodies has been studied in other species of *Mycosphaerella* (*6*, *7*, *8*, *25*), but the details of the development of perithecia of *M. cucumis* have not been reported previously. Study of several hundred monosporic isolates revealed that this fungus was strictly homothallic. The prompt development

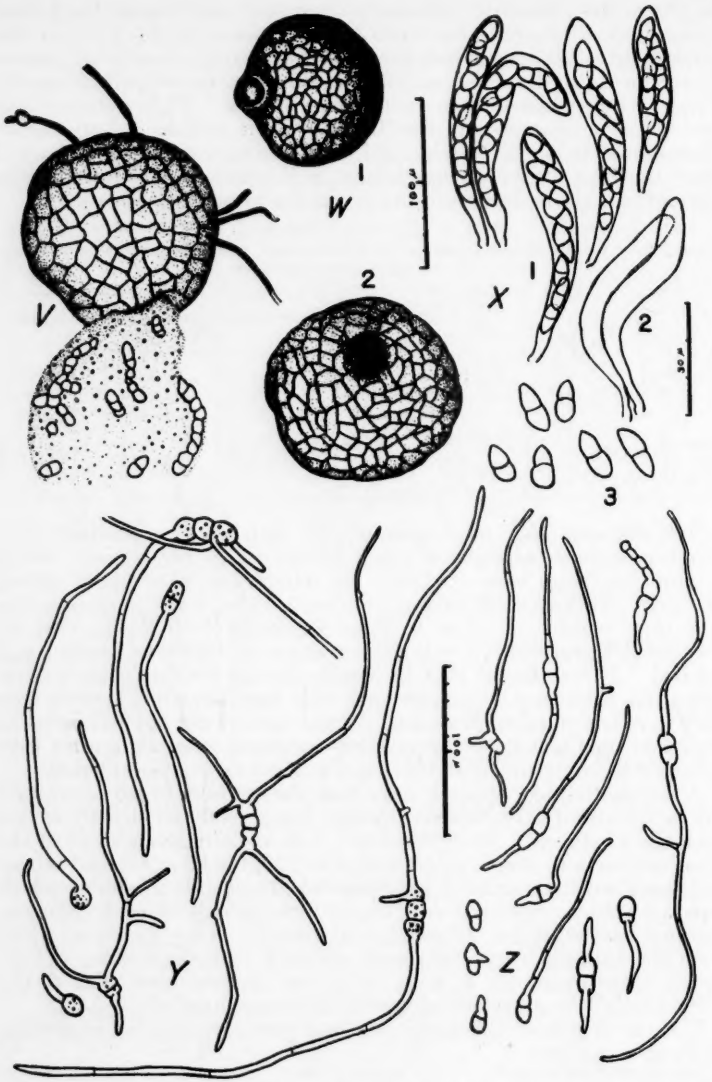

FIGURE 4.—*V*, Pseudoperithecium discharging granular contents and pseudoascospores. *W*, *1*, *2*, Mature perithecia. *X*, *1*, Mature asci with ascospores. *Y*, Pseudoascospores germinating (24 hours at 24° C.) in 2 percent orange extract. *Z*, Ascospores germinating in the same medium.

of pycnidia and perithecia in all fertile cultures facilitated the present studies. Observations were made on the cultures seeded at one side of oatmeal-dextrose agar plates. A young *B–a* culture was used because all three types of fruiting bodies were produced, aerial mycelium was absent, and the submerged mycelium grew relatively slowly. Sketches were made with the aid of a camera lucida.

Formation of pycnidia was initiated by the looping of the end of a main hypha or of its branch (fig. 5). As a rule, septation of the looping hypha increased as the size and number of coils increased. By the time three to five loops had formed, numerous slender hyphae with dense cytoplasm were developing from the inner surface of the entangled loops. These slender hyphae were possibly pycnosporal primordia which later developed into pycnospores. When more loops developed and a young pycnidium took form, the hyaline mycelium changed to yellowish brown. As maturity was approached, the color turned darker. The loops of a pycnidium in certain cases were contributed by different hyphae from the same thallus. One characteristic of the mycelium which was destined to form pycnidial loops was the presence of many swollen cells in the older part of the thallus. Such cells were elliptical or oval in shape and had very thin walls. The contents appeared to be very dilute and a few seconds' exposure outside the culture dish resulted in their immediate collapse. The early stage of loop formation was observed in both sporulating and nonsporulating isolates. In the latter the development ceased at the formation of loops and without the formation of pycnosporal primordia.

The first step in the development of perithecia was the formation of a terminal ascogonium that was nonseptate and had very dense cytoplasm (fig. 5). The ascogonium-bearing hypha was either straight or coiled. The antheridial hypha originating from a neighboring thick hypha of the same thallus was long and slender with granular, usually hyaline, cytoplasm. As the antheridial hypha made contact with the ascogonium, the latter began to become septate and coil around the terminal swelling of the former. The behavior of the nuclei was not studied. After intensive coiling and septation of the cells below the terminal cell, a rudimentary perithecium began to take form. The color of the external cells then turned olive brown. Accessory hyphae were sometimes observed. Because of the slenderness of these accessory hyphae, they were suspected of being trichogynes characteristic of certain other species of *Mycosphaerella*, but they were not visible at the time of contact of antheridium and ascogonium. Mature perithecia were finally observed, presumably after fertilization of the ascogonia.

In culture, the ascogonium sometimes failed to make contact with the antheridial hypha. In such cases, the mature "perithecia" failed to produce any asci and ascospores and, instead, chains of ascosporelike structures were formed. Further study would be necessay to establish whether or not there is a positive correlation between failure of the initial to develop into a perithecium and lack of fertilization. The chains eventually separated into sporelike bodies, each

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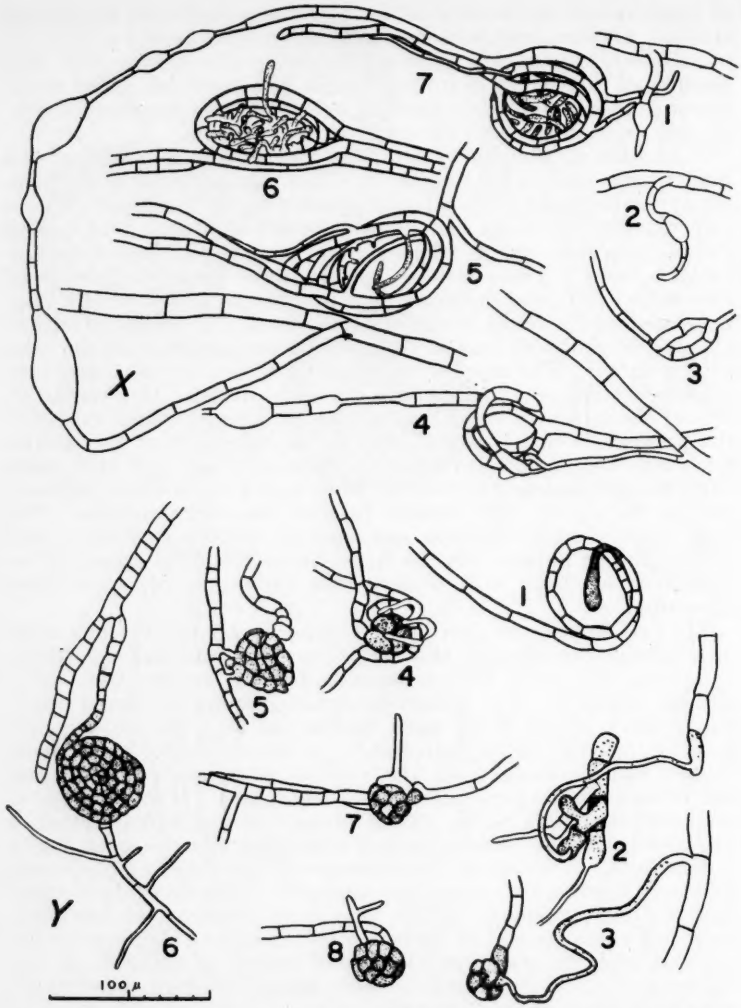


FIGURE 5.—Development of sexual and asexual fruiting bodies in a *B–a* culture on oatmeal-dextrose agar. *X*, Formation of pycnidium: *1*, *2*, fertile hyphae; *3*, early stage of loop formation; *4–7*, stages in development of pycnosporal primordia. *Y*, Formation of perithecium and pseudoperithecium: *1*, coiling ascogonium; *2*, antheridial hypha making contact with an ascogonium; *3*, swelling tip of the antheridial hypha with the ascogonium coiling around it; *4*, *5*, *6*, postfertilization stages; *7*, *8*, nonfertilized ascogonia developing into pseudoperithecia.

consisting of one to three cells. The cells were roughly spherical and the content was not so dense as that of ascospores. In reality these structures were homologous with pycnidia and pycnospores. In this paper the terms "pseudoperithecium" and "pseudoascospore" are applied to them.

SPORE GERMINATION

Pycnospores, ascospores, and pseudoascospores germinated readily in hanging drops of 2 percent orange extract (figs. 3, 4). Germination was very poor in sterile tap water.

The first step in the germination of pycnospores was the swelling of the cell to several times its original size. The second step was the formation of a hyaline germ tube. In the case of micropycnospores, a globular cell was usually formed at the tip of the germ tube, which either sent out a slender thread perpendicular to the axis of the germ tube or continued to grow and form another globular structure at the tip. In the case of macropycnospores, each cell of the bicelled spore sent out a germ tube which either remained nonseptate and nonbranched or became septate and branched immediately. Branching occurred at any point along the germtube. Secondary sporelike structures were sometimes found on the terminals of side branches similar to those observed by Grossenbacher (*4*). The ascospores and pseudoascospores germinated in the same manner as pycnospores except that there was no secondary sporelike structure at the tip of hyphae.

VARIABILITY OF CULTURAL CHARACTERS

In his recent studies of the black rot fungus, Wiant (*24*) reported isolates having various sporulating capacities and different cultural characters. In this investigation spores and hyphae were stained with 1 percent crystal violet for 1 minute, and the surplus stain was removed with distilled water and blotting paper. The preparation was cleared with 1 percent picric acid and then with clove oil. The cells of ascospores and pycnospores were shown to be uninucleate and those of the mycelium multinucleate. Since the fungus was homothallic and since individual thalli arose from uninucleate cells of spores, the nature of variability of the fungus was of particular interest.

Monosporic Isolations

The sporulating strains, *As*, *B–a*, and *B–1a*, were grown on oatmeal dextrose agar because of the profuse and early production of fruiting bodies. In general, pycnospores were picked from 7-day cultures and ascospores from 15-day cultures. The method was that used by Keitt and Langford (*11*), but no attempt was made to isolate the ascospores in their natural order.

A very dilute suspension of pycnospores was smeared over the surface of a potato-dextrose agar plate with a sterilized glass spatula. This seeded plate was incubated overnight at 24° C. When the germ tubes were beginning to protrude, spores were picked with a specially prepared glass needle under a binocular microscope. Only distinctly germinating spores were transplanted on oatmeal-dextrose agar plates. Six spores were usually arranged in a circle on one plate.

The incubation temperature was maintained at 24°. The cultural characters of the isolates were recorded and compared at the end of 1 week. Those with the same characters were grouped and given the same number.

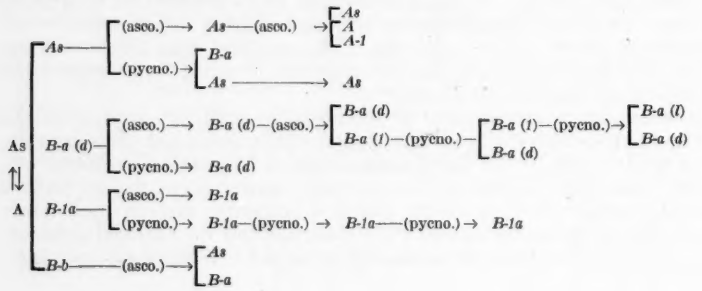
The first picking of 100 ascospores from the *As* strain yielded 99 *B–a* colonies and 1 *As* colony. The single *As* colony was transferred to oatmeal-dextrose agar and from it 112 ascospores were picked, of which 96.4 percent produced *As* colonies; 1.8 percent produced *A* colonies; 1.8 percent were of a new type, designated as *A–1*, which was a sterile albino with aerial mycelium similar to that of *A* and *As*. Each of 224 pycnospores picked from the original *As* strain yielded an *As* colony. Variants appeared to arise only from ascospores in this set of experiments, but the lack of variants from pycnospores may have been due to the relatively small number observed.

From 108 ascospores from strain *B–a*, only *B–a* colonies developed. From 80 ascospores from a *B–a* culture derived from an ascospore in the first picking only *B–a* colonies developed. About 20 percent of the *B–a* colonies were lighter in color than the rest. They were designated as *B–a(1)* and the others as *B–a(d)*. From 104 pycnospores isolated from a *B–a(1)* colony, 95 percent yielded *B–a(1)* and 5 percent *B–a(d)* colonies. From 112 pycnospores selected from a *B–a(1)* colony of the previous picking, 98 percent of the colonies were *B–a(1)* and 2 percent were *B–a(d)*. It appeared that *B–a(1)* was a mutant from *B–a(d)* and tended to throw frequent *B–a(d)* mutants.

From 140 ascospores from a *B–1a* culture all colonies were *B–1a*. In 3 successive monopycnosporic isolations covering a total of 416 colonies, all were true *B–1a* type.

Since the *B-b* culture in its early stage of growth showed a mosaic of characters of *B-a* type and *As* type and later developed *As* characters entirely, it was thought that possibly it came from an *As* ascospore but that a *B-a* mutation occurred in one of its young hyphae, and the mutant character was overrun by the rapid growth of the *As* of the mycelium. This supposition was shown to be true by a study of monoascosporic isolations from *B-b* type. From 75 monosporic colonies, 23 percent were *As* and 77 percent were *B-a*. No homogeneous *B-b* type cultures were secured by monoascosporic isolations from *As* or *B-a* type.

A diagrammatic summary of the type of culture secured by a study of single-spore lines follows:



Isolation by the Dilution-Plate Method

In order to observe a comparatively large population during a brief period, the dilution-plate method was used. Although this method had the disadvantage that two or more sporalings might grow together to form a single colony, the population that could be observed for variation was much greater than when individual spores were picked. Monosporic *As* and *B-1a* cultures were used in this test. The spore suspension of each culture was so adjusted that 1 milliliter of sterile water contained approximately 50 pycnospores of *B-1a* or 25 spores of *As*. One milliliter of the prepared spore suspension was pipetted aseptically into the oatmeal-dextrose agar plates and was made to spread evenly over the surface. Twenty plates of *As* and 30 plates of *B-1a* were made. All plates were incubated at 24° C., for 7 days in the case of *B-1a* and for 15 days in the case of *As*. The total number of colonies established in each plate was counted, and any colony that was slightly different from the parent culture in color and growth was recorded and isolated for further comparison both by mass transfer and by isolation of monopycnospores.

The total of resulting colonies from *As* was 371, of which 3 percent were *A* type, 1 percent were *B–1b* type, and 96 percent were *As* type. *B–1b* type was very similar to *B–1a* type, except that it assumed a deep olive-green color at an early stage of development. The difference between *B–1a* and *B–1b* types corresponded exactly to that between *B–a* (*1*) and *B–a* (*d*) types. Some monopycnosporic isolates of *B–1b* were uniform for type characters. Dilution plates of a *B–1a* culture yielded a total of 1,585 colonies, of which 0.4 percent was *B–1b* type and 99.6 percent *B–1a* type. A pycnospore suspension of a *B–1b* culture was prepared as in the case of *B–1a* and 100 dilution plates were made. Each of 5,126 colonies which developed was *B–1b* type. From this study it was evident that in monosporic cultures of *As* the type and number of mutants was greater than in *B–1a* cultures. The difference in color of *B–1a* and *B–1b* at the early stage of development was slight, and it disappeared as the colonies grew. The results with the dilution-plate method were similar to those obtained from monosporic isolations.

Isolation of Mycelial Cells

The frequent occurrence of *As* sectors and the sudden appearance of *As* fruiting bodies in *A* cultures led to consideration of the variability arising from nuclear changes in mycelial cells. Since the *A* culture was obtained from early monosporic isolations, the purity of the culture was beyond question. The problem to be solved was the uniformity in the genotype of the cells of the mycelium that might be detected by phenotype analysis. In order to render such study feasible, the isolation of mycelial cells at random was carried out.

Two *A* cultures from monopycnosporic isolation from the natural host substrate were available. One was 1 year old, the other was 1 month old. The mycelium of these cultures was removed and washed several times with sterile water. The washed mycelium from one plate culture of a given isolate was minced aseptically for 15 minutes in a Waring Blender. To 1 ml. of the resulting mycelial suspension was added 9 ml. of sterile water. Then with the aid of a

sterile glass spatula, one drop of the suspension was smeared over a potato-dextrose agar plate. The technique for picking spores was again used in the picking of mycelial cells. Only those pieces of hyphae which consisted of two to three cells were picked and transplanted to oatmeal-dextrose agar plates. Plates were incubated at 24° C. and records were taken at the end of the seventh day when fruiting bodies were appearing on certain colonies.

In the case of the 1-year *A* culture, a total of 96 pickings was made. Only 24 percent of these pickings developed into colonies. Among the developing colonies, 87 percent were *As* type and 13 percent *A* type. A total of 53 pickings was made from the 1-month *A* culture. All of them developed into colonies, of which 68 percent were *As* type and 32 percent *A* type. The variation of the *A* type culture to the *As* type and vice versa occurred naturally and spontaneously. It was not possible to separate these 2 types and propagate them in their own characters indefinitely.

RELATION OF MEDIUM TO GROWTH AND SPORULATION

In an attempt to induce sporulation of the fungus, Wiant (*24*) employed a number of media including corn-meal agar, oatmeal agar, and cucurbit stems. Sporulation was scant in each of these, only a few fruiting bodies appearing occasionally. In the studies just reported sporulation was governed by genetic factors. However, it was of interest to determine whether sporulation in the sterile type *A* could be induced by the nutrient. The agar media used are listed in table 3. Dextrose and peptone were used at the rate of 10 grams per liter. Other ingredients were used at rates indicated elsewhere (*16*).

TABLE 3.—*The effect of various agar media on sporulation of an A type culture of Mycosphaerella cucumis*

Medium	Average growth rate	Color of the substratal mycelium	Aerial mycelium [2]	Sporulation at 144 hours
	Mm. per hour			
Potato	0.53	Pale olive	+	None.
Potato-dextrose	.91	Dark greenish black	+++	Do.
Potato-peptone	.84	Salmon	++	A few.
Corn meal	[1].75	Pale olive	+	None.
Corn meal-dextrose	.72	Greenish black	++	A few.[3]
Corn meal-peptone	.79	Salmon to brownish	+++	Sparse.
Czapek's solution	[1].96	Colorless	−	None.
Czapek's solution-dextrose	.79	Dark olive	+++	Sparse.
Czapek's solution-peptone	.53	Salmon	+++	None.
Czapek's solution dextrose-peptone	.86	Yellowish brown	++++	Sparse.
Bean	.86	Brownish olive	−	None.
Bean-dextrose	.97	Dark olive green	+++	Sparse.[3]
Bean-peptone	.67	Purplish	+++	None.
Bean-dextrose-peptone	.79	Brownish	+++	Sparse.[3]
Oat-paste	.92	Dark greenish black	+++	Abundant.[3]
Oat-paste-dextrose	.79	Dark greenish black	+++	Do.[3]
Oat-paste-peptone	.79	Pale yellowish brown	+++	None.
Oat-paste-peptone-dextrose	.92	Brown	++++	Abundant.
None	[1].57	Colorless	−	None.
Dextrose	.82	Pale olive	−	Do.
Peptone	.39	Salmon	+++	Do.
Dextrose-peptone	.90	Brownish	++++	Do.

[1] Mycelium was weak and sparse.
[2] −=none; + to ++++ indicate increasing amounts of aerial mycelium
[3] Primordial and mature perithecia also occurred

An *A* culture from a monopycnosporic transfer from the *As* type was used. Five plates of each culture medium were incubated at 24° C. for 144 hours. Sporulation, rate of growth, color of the submerged mycelium, and extent of aerial mycelium were recorded.

The results in table 3 show that the growth was most rapid when dextrose was present. In a synthetic medium, such as Czapek's solution, best growth occurred with dextrose and peptone. The peptone-dextrose effect was less significant in media rich in organic materials. The presence of dextrose induced olive to greenish-black color while peptone induced salmon to purplish-brown color of submerged mycelium. Peptone usually induced more vigorous aerial mycelium than dextrose, but the most abundant development occurred when both were present.

Sporulation was relatively abundant only on oat-paste agar and when dextrose alone was added to the latter, but it was prevented when peptone alone was added. When dextrose was added with peptone the inhibitive effect of the latter was prevented. Sparse sporulation occurred on bean-peptone dextrose and on corn meal-peptone agar; it was rare on corn meal-dextrose and potato-peptone agars. When sporulation occurred, the cultural characters were very similar to those of *As* cultures. In earlier experiments it was shown that pycnidial loops occurred in all sterile cultures but development usually ceased before sporulation. It is possible, therefore, that the presence of certain nutrients or growth factors in the media mentioned enabled the *A* mutant to become as fertile as the wild type, *As*. Evidence has already been presented that the *As* type might exist in *A* cultures without expressing itself; it is possible, therefore, that the oat-paste medium promoted the growth and expression of the *As* type which was already present. Nevertheless, when the above media were used for culture of other sterile strains (*A–1*, *A–2*, and *B–3*) no sporulation was ever observed, although pycnidial loops were common. This difference may be due to a difference in the nutritional requirements of mutants.

EFFECT OF IRRADIATION ON SPORULATION

The effect of irradiation on the sporulation of fungi has been reported by Stevens (*21*, *22*, *23*) and by Ramsey and Bailey (*15*). In the present investigation 7-day *A* cultures on potato-dextrose agar plates, showing vigorous aerial mycelium, were irradiated with a mercury-quartz lamp (Westinghouse Sterilamp). The plates were placed 6 inches below the source of light with covers removed. The intervals of treatment were ½, 1, 5, 10, 15, 20, 30, and 40 minutes. After the treatment, all plates were kept in complete darkness at 24° C. The nonirradiated plates served as controls. On the fourth day after irradiation, sporulation occurred in plates irradiated 1 minute to 40 minutes, being most abundant in the 15-, 20-, and 30-minute treatments. None of the control plates showed a trace of fruiting bodies. The aerial mycelium of the irradiated cultures had all turned gray and collapsed while abundant black pycnidia appeared amongst the collapsing mycelium. The pycnidia were very similar to those of the *As* culture.

A series of experiments was then carried out on the media listed in table 3. In addition to sporulation on oat-paste agar, as shown earlier to occur without irradiation, the amount of sporulation was increased on those media in which it occurred only sparsely without irradiation. The most significant effect, however, was on potato-dextrose agar on which no sporulation occurred normally. A slight amount of sporulation appeared on corn-meal agar. The relative number of perithecial primordia remained constant on oat-paste agar, oat-paste-dextrose agar, and bean-dextrose agar in both irradiated and nonirradiated plates, but the maturity of the perithecia was hastened and the proportion of mature perithecia to pseudoperithecia increased with irradiation. When potato-dextrose agar plates were irradiated before they were seeded, no sporulation occurred in the subsequent culture. When *As* cultures were irradiated, the amount of sporulation was not affected.

INDUCTION OF MUTATION BY IRRADIATION

Since spontaneous mutation was observed frequently in the *A* and *As* cultures, the possibility of increasing the frequency and direction of mutation by irradiation with ultraviolet rays was considered. The mercury-vapor type of lamp (General Electric AH–6,100 watts, and 500 volts alternating current) was employed. The wave length was 2,534 Å. and the constant temperature in operation was 25° C. A pycnospore suspension from an *As* culture at a density of approximately 7,500 spores per milliliter of sterile distilled water was used. Ten milliliters of the spore suspension was pipetted into the radiation cell. Before irradiation, 0.2 milliliter was drawn out from the cell and diluted in 100 milliliters of sterile distilled water as a control. After starting the irradiation, 0.2 milliliter of the spore suspension was drawn out and diluted at 10-minute intervals up to 80 minutes. From each dilution of these treatments 10 plates were prepared with 1 milliliter of suspension. All plates were incubated at 24° and records were taken at the end of 6 days. Special attention was given to types of colonies that had not been observed previously.

The percentage of viable spores yielding *A*, *As*, or *B-b* cultures decreased rapidly as the duration of irradiation increased. The mutant, *A–1*, previously observed in monosporic isolations, appeared regularly throughout the treatments. *B–1b* type, which had been isolated by the dilution-plate method from *B–1a* cultures, appeared at 10-minute radiation. Three mutants (*A–2*, *A–2s*, and *B–3*) which had not been observed before, were found. *A–2* appeared first after 10 minutes' irradiation but was more frequent after 30 to 60 minutes. *A–2s* appeared only once and then after 70 minutes' irradiation, while *B–3* appeared at between 40 and 50 minutes. *A–2* and *A–2s* were quite similar; the former was a sterile albino, the latter sporulated and was white at first, turning brown with age. The pycnidia produced in *A–2s* were peculiar in type, since they were usually grouped together to form sclerotiumlike bodies in which several pycnidia were united at the base but were distinct otherwise and had distinct ostioles. The black sclerotiumlike bodies were 0.5–3 millimeter in diameter. The mass of pycnospores discharged at the ostioles was whitish instead of the usual grayish salmon. Type *B–3* grew very

slowly and had thick velvety to woolly aerial mycelium. Both aerial and submerged mycelia assumed a purplish-brown color. No mature fruiting bodies were observed, but microscopic study revealed that the loop formation characteristic of the early stage of normal pycnidial development was present. Nevertheless its development stopped before the formation of a pycnidial wall. Colonies of the mutants described above are illustrated in figure 1.

As shown in figure 6, the percentage of killing caused by irradiation increased rapidly up to 20 minutes. The differences in the percentage of killing at intervals above 20 minutes were not significant. The percentage of mutants in the surviving spores increased rapidly up to 40 minutes' exposure beyond which the rate slowed down. The dif-

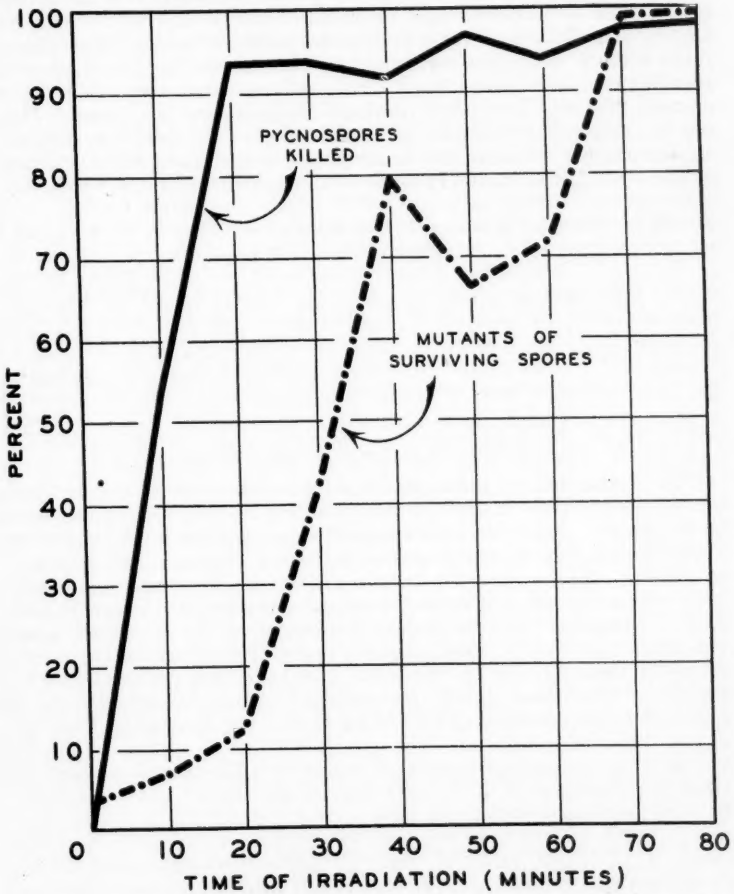


FIGURE 6.—Effect of irradiation on killing and on mutation of pycnospores of *Mycosphaerella cucumis*.

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ference in percentage of mutation at 70 to 80 minutes and 40 to 60 minutes is probably not significant since the population of spores which survived the two longest treatments was very small.

INDUCTION OF MUTATION BY HIGH TEMPERATURE

It was observed during very warm summer periods that *A* sectors appeared more frequently than usual in monosporic isolates from *As* cultures. Experiments were conducted, therefore, to determine whether temperature influenced the rate of mutation. Two young monosporic cultures were incubated at 24° C. for about 10 days, when fruiting bodies were well formed. Then 1 of the plates was removed to an incubator at 36° C., the other to an incubator at 16°. At the end of 1 week, 10 dilution plates for each treatment were made. All these plates were again incubated at 24° for 1 week, and then the number and type of colonies were recorded. The data in table 4 show that the frequency of *A* mutations in *As* cultures was greatly increased after high temperature treatment. The *B–1a* mutant also occurred after the high temperature treatment. These results, incidentally, offered an explanation of the fact that difficulty was commonly encountered in maintaining the sporulating character of the *As* cultures in the laboratory during warm summer periods.

TABLE 4.—*The effect of temperature on mutation as shown by the percentage of colonies in type classes*

Treatment °C.	Total colonies	Colonies in type classes—			
		As	*A*	*B–a*	*B–1a*
	Number	*Percent*	*Percent*	*Percent*	*Percent*
16	239	98.3	1.7	0	0
36	178	39.4	59.7	0	1.6

TAXONOMIC POSITION OF THE FUNGUS

The present study shows that the imperfect stage of the fungus is extremely variable in size of pycnidia and in size and septation of pycnospores. Moreover, considerable variation in these characters occurs as a result of genetic mutation and the segregation of mutants in culture. This accounts for the confusion in the taxonomic position of the fungus cited in the introduction of the paper. Since Fautrey and Roumeguére (*17*) published the name of the imperfect stage, *Ascochyta cucumis*, in 1891, slightly earlier than that of the perfect stage by Passerini (*18*) in the same year, the first specific name has priority. Therefore the proper binomial of the fungus should be *Mycosphaerella cucumis* (Fautr. and Roum.) nov. comb. The synonymy follows:

Ascochyta cucumis Fautr. and Roum., 1891.
Didymella melonis Pass., 1891.
Phyllosticta citrullina Chester, 1891.
Ascochyta citrullina (Chester) C. O. Sm., 1905.
Sphaerella citrullina (Chester) C. O. Sm., 1905.
Diplodina citrullina (C. O. Sm.) Gross., 1909.
Mycosphaerella citrullina (C. O. Sm.) Gross., 1909.
Ascochyta melonis Potebnia, 1910.
Sphaerella melonis Ferraris, 1912.

DISCUSSION

Although Fautrey and Roumeguére (17) recognized the cucurbit black rot fungus on a variety of Chinese cucumber to be a species of *Ascochyta* and described it under the name *Ascochyta cucumis* in France as early as 1891, the pleomorphism of this fungus caused some confusion in its classification. The small continuous micropycnospores which predominate in nature on the host apparently led Chester (*2*) to describe the fungus as *Phyllosticta citrullina* on watermelon and led Keissler (*10*) to report *Phyllosticta orbicularia* Ell. et Ev. on *Cucumis melo* L. Grossenbacher (*4*) stated that Chester's specimen of *Phyllosticta* might not represent the same pathogen as that described later by C. O. Smith as *Ascochyta citrullina*. The explanation of this discrepancy is found in the fact that this organism may at times produce pycnospores which conform to the genus *Phyllosticta*. Inclusion of the perfect stage of *Ascochyta* in *Didymella* is questionable, even though Passerini (*18*) and Klebahn (*13*) claimed that paraphyses were present. Ferraris (*3*) and American workers (*4, 19, 24,*) did not see any paraphyses among the asci of this fungus. The present observations show that no paraphyses are present in the perithecia but that immature or abortive asci are often present among the mature asci. The abortive asci might have been interpreted erroneously as paraphyses. In view of the priority of *Ascochyta cucumis* Fautr. and Roum., the name of the perfect stage is designated herein as *Mycosphaerella cucumis* (Fautr. and Roum.) nov. comb.

The production of micropycnospores and macropycnospores varied with the strain and the media. Thalli from micropycnospores gave rise to colonies with mature perithecia. In spite of evidence obtained in other species of *Mycosphaerella* that micropycnospores function as spermatia, it is believed that they function as conidia in the black rot fungus.

Homothallism of this genus was first noted by Jones (*9*) and later proved by Hare and Walker in *Mycosphaerella pinodes* (Berk. and Blox.) Stone (*5*). The present pathogen also is homothallic. Fertilization of the ascogonium is accomplished by an antheridium originating from a neighboring hypha of the same mycelium.

Cells of both ascospores and pycnospores were shown to be uninucleate, while those of the mycelium were multinucleate. Wiant's culture from Hubbard squash conforms to the *As* type described herein; his sector of the squash isolate is similar to the *B–1a* and *B–1b* types; his isolate from Puerto Rican cucumber is similar to the *B–a* type. These variants, according to the present studies, originate from the *As* wild type. Wiant also observed the sterile *A* type but failed to point out that *As* and *A* types are spontaneously and reversibly mutable.

The mutability of the *As* strain is high and the direction of mutation is various. The frequency of mutation may be increased by high temperature and by irradiation. That the repeated transferring of mycelium of species of *Ascochyta* increased the sterility of the subsequent cultures has been noted by many workers, including Yu (*26*). This was also observed in the *As* strain. A possible explanation is that the repeated picking of mycelium may greatly increase the probability of purifying the *A* mutant from the *As* strain, since most *As*

mycelium is producing spores and grows less rapidly than that of the mycelial mutant.

Wiant failed to induce sporulation of the culture by the use of different media (*24*). The sporulation of this fungus seems to be controlled by both genetic and nutrient factors as in the case of *Neurospora* (*1*). The loss of the property of synthesizing certain organic substances necessary for sporulation may be responsible for some of the sterility, and may explain the inconsistency in sporulation of the usually sterile *A* type. By using fertile strains, such as *As* and *B-1a*, sporulation was readily obtained on all media that Wiant had tried without success.

It is interesting to note that the sterile *A* strain can be induced to sporulate by irradiation of a potato-dextrose culture for 1 to 40 minutes under a mercury-quartz lamp. Ramsey and Bailey (*15*) were able to induce the sporulation of *Fusarium cepae* (Hanzawa) Link and Bailey and *Macrosporium tomato* Cooke by irradiation, and they were of the opinion that it was not due to inhibition but rather to stimulation. Since in the present work the fruiting bodies are exclusively of the *As* type and since *A* and *As* are reversibly mutable, it remains to be determined whether or not irradiation increased the rate of mutation of *A* type to *As* type.

SUMMARY

The perithecia, pycnidia, and pseudoperithecia of *Mycosphaerella cucumis* as well as the spores produced by them, are described. The perithecia varied in size within a much narrower range than the pycnidia. Two types of pycnidia are described. One produced small continuous spores (micropycnospores); the other produced larger spores (macropycnospores) which were continuous, one-septate or rarely two-septate. The types of pycnidia were indistinguishable morphologically except for the size and septation of the pycnospores produced.

Ascospores and pycnospores were uninucleate. Monosporic lines were homothallic. The developmental histories of the sexual and asexual fruiting bodies are described. There was no evidence that micropycnospores functioned as spermatia.

The wild type, *As*, was extremely variable. It mutated spontaneously to *A*, *A–1*, *B–a*, *B–1a*, and *B–1b*. *A* and *A–1* were sterile, while *B–a*, *B–1a*, and *B–1b* sporulated profusely and produced mycelium sparsely. Mutant *A* tended to mutate back to *As* while *A–1*, *B–a*, and *B–1a* were very stable. *B–1b* was apparently a variant of *B–1a* from which it differed only in the early development of the color of the colony. The growth rate and coloration of the submerged mycelium of the fungus varied with the medium. Dextrose in combination with peptone in any kind of medium favored vigorous mycelial growth. Dextrose was responsible for the olive-green color of the submerged mycelium, while peptone induced a salmon to purplish-brown color.

Sporulation of sterile strain *A* was induced on oat-paste agar and by irradiation of a well-developed culture on potato-dextrose agar medium for 15 minutes.

Irradiation with ultraviolet rays induced a higher frequency of mutation and new mutants. *A–2*, *A–2s*, and *B–3*, were obtained by this means. *A–2* and *B–3* were sterile while *A–2s* produced spores in sclerotiumlike groups of pycnidia.

Exposure to a temperature of 36° C. for 1 week resulted in an increase in the number of mutants.

The confusion in earlier literature regarding the taxonomy and nomenclature of this organism is probably due largely to its pleomorphism. Size, shape, and septation of pycnospores and size of pycnidia are extremely variable. The earlier reports of paraphyses in the perithecium are probably due to erroneous interpretations of immature or abortive asci. According to the information available the proper Latin binomial for the fungus is *Mycosphaerella cucumis* (Fautr. and Roum.) Chiu and J. C. Walker.

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RELATION OF SPECIFIC GRAVITY TO SHRINKAGE AND OF THESE FACTORS TO GROWTH IN YELLOW POPLAR[1]

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INTRODUCTION

In recent years a number of investigations have been made to determine the physical properties of various woods and the effect of rate of growth and of certain conditions of growth on these properties. Relatively little work has been done, however, on native diffuse-porous woods, nor has an intensive analysis of relationships been made.

Yellow poplar (*Liriodendron tulipifera* L.), an important Appalachian hardwood and the species used in this study, has been studied by several researchers. Paul and his coworkers (*4*, *5*, *6*) [2] have given us much of the information now available on the relation of the rate of growth to the specific gravity of the wood produced. Paul (*4*) reported that prolonged suppression of growth resulted in a lowering of the specific gravity of the wood, whereas improved growth conditions in slow-growth virgin trees resulted in an increase in specific gravity. The wood of young trees (70 to 150 years of age) in old-growth stands was heavier than in the old-growth trees (150 to 300 years) of the same stand (*6*). The slightly lower average specific gravity obtained in the second-growth trees as compared to young trees in old-growth stands was explained by the presence of wide annual rings made up of wood of low specific gravity near the pith in trees that had started growth in rather open stands. Paul and Norton (*6*) reported that there was not a very close relationship between rate of growth (rings per inch) and specific gravity in yellow poplar. Nevertheless, they found the rate of growth to be useful in determining the quality of wood if the history of its development was taken into consideration. No definite correlation was established between specific gravity and factors such as climate, soil, and elevation.

Boomsliter (*1*) and Stern (*7*) have studied the mechanical and physical properties of yellow poplar. Their results are based on one or two trees in each case.

This report is intended to check some of the published data and conclusions; to determine quantitatively certain results that have been reported qualitatively only; to include and correlate properties not hitherto studied, such as shrinkage; and to limit the samples to one area of representative commercial stand and thus eliminate possible differences between areas.

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[2] Italic numbers in parentheses refer to Literature Cited, p. 127.

EXPERIMENTAL PROCEDURE

The samples of yellow poplar were obtained from 23 trees on a 200-acre tract in Preston County, W. Va., located in the north-central part of the State. The area is mountainous with steep slopes. The stand was classified as cove hardwood type; the yellow poplar was in mixture with other hardwoods. The samples were collected while the tract was being logged and represented the trees from near the ridges down to the creek bed, or a range of elevation from 1,750 to 2,150 feet. The site is classed as good (site II). The exposure was south to southeast.

One disk, from 6 to 8 inches thick, was sawed from each tree. In 16 of the trees, the disks were taken just above a 16-foot log. In some cases it was necessary to saw off the butt or make a short log first. In 4 trees the disk was sawed off at 8 feet above the stump, in 2 trees at 10 feet, and in 1 tree, at 12 feet. The age of the trees at the height of the test blocks ranged from 130 to 260 years, except one of 78 years; at stump height, the age ranged from 86 to 273 years. If the disk were not to be cut up immediately, they were placed in the cold room at 40° to 42° F. until used. The annual rings were counted and marked on the cross section. Blocks approximately 1 by 1 by 3 inches were sawed from each disk on the north and south diameter. Care was taken to have the fiber alinement parallel to the long axis of the block. When interlocked grain or fluctuating slope of spiral grain was present, the weighted average of the grain slopes was used. Two parallel sides of the block were at right angles to the annual rings; the other two sides were parallel to the rings.

The dimensions of the blocks were measured by a dial-gauge instrument (fig. 1) especially designed and constructed for this purpose. With this instrument, the place of measurement can be marked by drawing a pencil part of the way round the gauge stem and subsequent measurements of the block can be made at the same place. With this instrument it is possible to measure easily and rapidly and to be sure that the same spot will be used in each measurement. If the block is not absolutely square, the use of the same spot in each measurement is very important. To obtain average values with blocks that are not uniform in ring width, it is better to measure at two or more points across the radial surface. Otherwise, the rings-per-inch value which is indicated at the point of measurement should be used. This caliper instrument reads to 0.001 inch throughout a range of 1 inch and is fully as accurate as a vernier caliper. Accuracy is assured by the sensitivity of the gauge, the easily readable dial, which eliminates the eye strain and guessing required to read a vernier scale, and the constant contact pressure of the gauge on the object for a given thickness.

The green volume of each block was determined by suspending it in a beaker of water of known weight and weighing the volume of water displaced. The blocks were then dried very slowly in an experimental dry kiln. Loss of weight was determined by weighed samples. The drying temperature was from 100° to 110° F. Final drying to a moisture content of zero percent was done in an electric oven at 216° F., again in easy stages of drying. After reaching constant weight, the blocks were cooled in a desiccator containing P_2O_5, weighed,

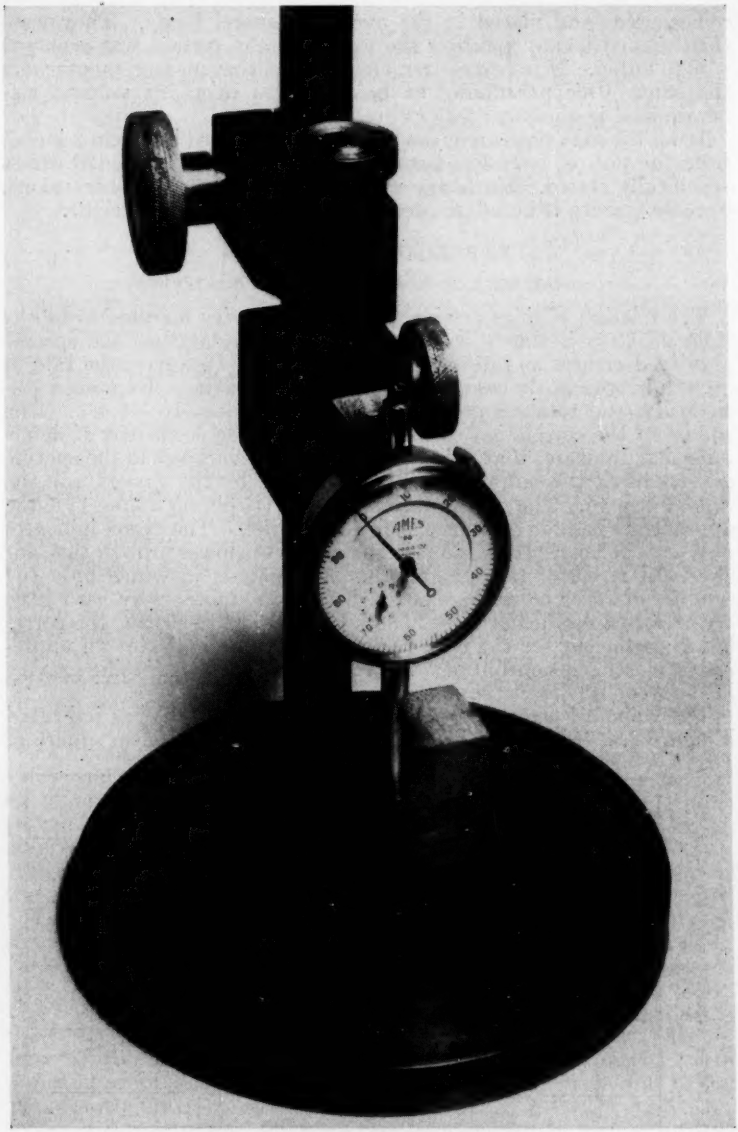

FIGURE 1.—Adjustable dial-gauge caliper for measuring changes of the dimensions of a block.

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remeasured, and placed in the oven for several hours. They were then dipped in hot paraffin; the excess on the surface was removed while molten. If no excess remained, dimension measurements were the same after paraffining as before. The oven-dry volume was determined in the same way as green volume.

In all the data presented, the blocks that averaged less than 2 inches from the pith or were less than 20 years old are not included unless specifically stated. Shrinkage values are based on green dimensions. Specific gravity is based on green volume and oven-dry weight.

EXPERIMENTAL RESULTS

I. RINGS PER INCH AND SPECIFIC GRAVITY

The relation of rings per inch to specific gravity for the 345 blocks from 23 trees is shown in figure 2. It is evident that the specific gravity decreases as rate of growth decreases. However, the rate of growth is not closely associated with specific gravity. Expressed statistically, the total or gross correlation coefficient is -0.483. The square of the correlation coefficient, which is the coefficient of determination, indicates that only 23 percent of the variance in the specific gravity of all the samples could be explained by the variation in the rate of growth. The first equation in table 1 (column 5, line 1) is the appropriate one for the curve shown in figure 2. The graph indicates a somewhat better correlation in the region of slower growth than for the total range of rate of growth. An analysis in which only the samples of 20 or more rings per inch (74 in number) were used gave a correlation coefficient of -0.588. Compared to -0.483, the correlation coefficient for the entire curve, this value indicates an appreciably closer relationship between rate of growth and specific gravity in the wood of slower growth.

The standard error of estimate of Y, specific gravity, as indicated in figure 2, is ± 0.027. This is the square root of the mean square of

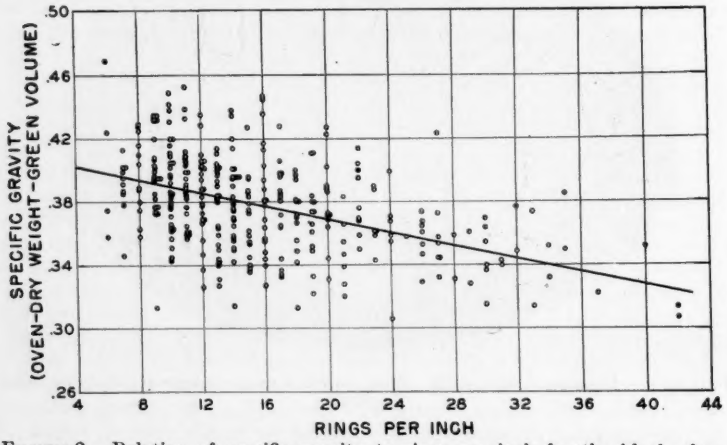

FIGURE 2.—Relation of specific gravity to rings per inch for the blocks from 23 yellow poplar trees.

errors of estimate. The chances are about 95 out of 100, therefore, that a specific gravity value, estimated from the first equation for a given value of rings per inch, will not be in error by more than ± 0.054 (twice the standard error).

A statistical summary of the data is presented in table 1.

TABLE 1.—*Analysis of covariance of rings per inch and specific gravity, together with regression equations and correlation coefficients*

Source of variation	Degrees of freedom	Sum of squares	Mean square	Regression equation	Correlation coefficient	Degrees of freedom
General regression	1	0.0742	0.0742	$Y=0.412-.0020X$	-0.483^{**}	343
Between tree regressions	22	.0150	.00068**			
Between tree means	22	.1242	.00565**	$Y=.408-.0018X$	$-.290$	22
Error (within trees from individual regressions)	299	.1043	.00035			
Between tree regressions+error (within trees, from average regression)	321	.1194	.00037	$Y=.413-.0021X$	$-.588^{**}$	321

**Highly significant.

The range of the correlation coefficients for the blocks of the individual trees was 0.479 to -0.893. The range for the regression coefficients was 0.0024 to -0.0070. Twenty of the coefficients were negative values; 3 were positive. These values show the great variability found between trees in the relation of rate of growth to specific gravity.

The average specific gravity, including heartwood and sapwood, was 0.378. The standard deviation was ± 0.030.

The correlation between means of trees was low (-0.290). Testing by the null hypothesis shows this value to be below the 5-percent level, or nonsignificant, which indicates that there is no reliable association between the average specific gravity of each of the trees and their average values of rings per inch. This conclusion is confirmed by an analysis of error variance of the sum of squares of tree means of specific gravity, Sy^2, and reduction of Sy^2 due to regression. The F value of mean square of reduction divided by the mean square of the difference is nonsignificant. Hence, the different average values of growth rate of the trees did not account for any significant amount of the variance in average specific gravities.

To determine whether the average growth rates of the trees were significantly different, rings per inch, X, were tested by analysis of variance. The F value obtained proved that the original tree means rings per inch were highly significantly different from each other. It was found further that when analyses of variance was applied to the actual tree means of specific gravity, Y, those means were highly significantly different. After the means of specific gravity were adjusted to an average value of rings per inch, they were still highly significantly different, as is shown in table 1.

The mean square of the variation between tree means of specific gravity is the average variation between the means after they are adjusted to an average level of growth rate, X. When compared to experimental error with 321 degrees of freedom by the F test, this mean square (0.00565) is found to be highly significant. This indi-

cates that the tree means of specific gravity do not change regularly with mean rings per inch, but are definitely erratic. The growth rate does not explain the differences among tree mean specific gravities; after the mean specific gravities of the trees are adjusted to an average growth-rate basis, they still differ significantly from each other. Evidently, other biological forces influence the average specific gravity of a tree more than does the average growth rate within the range studied. One reason for this may be a lag in response of specific gravity to changes in growth rate, although a study of the data of the individual tree samples does not place much weight on this factor. Age may have a small effect in some trees, as will later be shown. It seems likely that inherent or hereditary characteristics may be responsible to a large degree for wide differences in adjusted mean specific gravities of trees, granting that ecological factors would exert a modifying influence.

The differences between tree means also are responsible for some of the total variance between rings per inch and specific gravity when all the blocks are considered as a random sample as in figure 2. The low between-tree correlation coefficient, with its attendant large sum of squares of error of estimate resulting from variation of tree means, offsets the higher within-tree coefficient to give the intermediate coefficient of total correlation.

The average correlation coefficient (the appropriate average of the 23-tree correlation coefficients), based on the average within-tree regression, is -0.588. Correlation of rings per inch to specific gravity within the trees after eliminating the effect of differences among the tree means of rings per inch and specific gravity, is considerably better than that for the mean values of the trees. However, since rings per inch, in average regression, accounts for only 34.5 percent (r^2) of the variance in specific gravity within trees, this relationship is fairly low.

The above considerations indicate that for flat-sawn inch boards selected at random, some relation between rings per inch and specific gravity for the individual pieces would be expected ($r=0.483$). For thicker cuts, less association would be probable, and for large timbers, very little or no significant correlation would be expected between the mean values of the individual timbers, since the larger cuts more nearly approximate the conditions of the separate trees in which a lower correlation of -0.29 exists.

The mean square of between-tree regressions (line 2, table 1) is an average of the variation in specific gravity that is not explained by the regular effect of changing growth rate within each tree upon the specific gravity. The individual tree coefficients of regression or rates of change of specific gravity with rings per inch are significantly different from each other and from the average regression or slope. An average slope, such as that indicated by the regression coefficient in the third equation in table 1, does not give a true representation of all the individual trees. The individual slopes shown in figure 3, differ from the best average slope for the group more than would be expected from trees taken from a homogeneous population. There appear to be inherent differences between the trees that cause some of them to be rather unlike others in this relationship

of growth rate to specific gravity. This difference, however, is apart from the differences in levels of the curves, i. e., the differences in the tree means of Y (specific gravity).

The sum of squares of errors of estimate, 0.015 with 22 degrees of freedom, is associated with the variation of the tree regression coefficients, or the failure of the individual tree regressions to coincide with the average within-tree regression. This is the difference between the sum of squares of errors of estimate for variation within trees from average regression and the corresponding value for variation within trees from individual regression. The mean square 0.00068 for regressions is tested by the F test against the mean square of deviations from individual tree regressions with 299 degrees of freedom (line 4, table 1). The mean square of deviations is an average of the variation in specific gravity not explained by tree differences of X and Y or by individual regressions. The quotient was found to be highly significant. Hence, an average slope of curve does not adequately represent the individual slopes.

The regression line for each tree is shown in figure 3. This figure illustrates the variability discussed above regarding the differences between the slopes of curves for the individual trees, the differences between levels of the curves, the range of rings per inch and specific gravity for each tree, and gives the correlation for the regression line of each tree.

The first equation in table 1 (column 5) represents the curve shown in figure 2 for the total correlation where Y is specific gravity and X is rings per inch. From a practical standpoint, this is probably the equation of most importance because it represents the average relation between rings per inch and specific gravity that might be expected if samples were taken from a pile of lumber. The second equation expresses the curve that would be obtained for weighted mean values of rings per inch and specific gravity for the individual trees. The

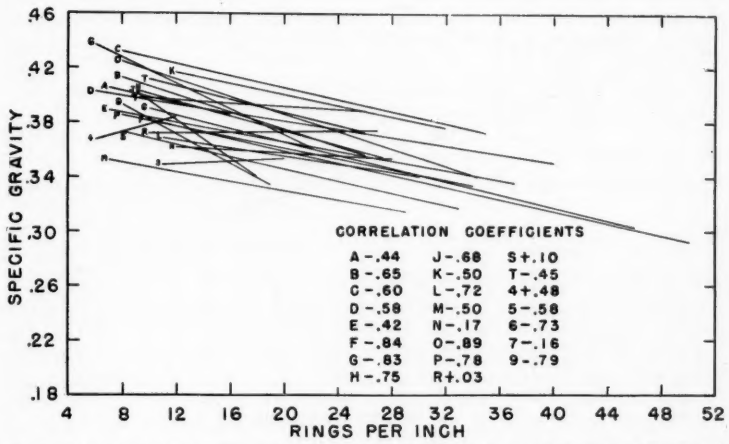

FIGURE 3.—Individual regression lines and correlation coefficients for specific gravity and rings per inch of 23 yellow poplar trees.

third equation expresses the average of the individual tree regressions shown in figure 3. This equation is based on the means of X and Y for all the samples and the average within-tree regression coefficient for the 23 trees. It represents the average relations between rings per inch and specific gravity that exists within the trees after correcting for the differences among the means of the trees.

In the light of the results recorded above, it is evident that the biological forces which cause a within-tree relationship are not those which cause different trees to have different specific gravities.

II. RINGS PER INCH AND VOLUMETRIC SHRINKAGE

Figure 4 shows the experimental data for rings per inch and volumetric shrinkage of all the blocks. The standard error of estimate of volumetric shrinkage for the total regression is ± 0.961 percent. An inverse relationship was obtained, as would be expected, because of the inverse association of rings per inch with specific gravity (fig. 2).

A statistical summary of the data is given in table 2.

The mean square for differences between tree regressions tested against experimental error (item 4) shows that these regressions or slopes are significantly different from each other, although the probability value is just at the 5-percent level. This shows less variation among the slopes than was found for rings per inch and specific gravity. The tree slopes are so similar that they can almost be considered as coming from a uniform group and as fitting quite well an average slope.

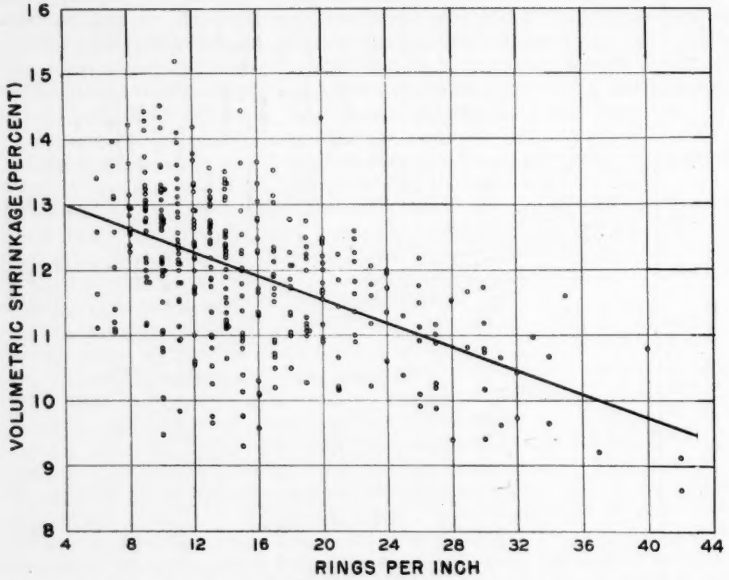

FIGURE 4.—Relation of volumetric shrinkage to rings per inch for the blocks from 23 yellow poplar trees.

TABLE 2.—*Analysis of covariance of rings per inch and volumetric shrinkage together with regression equations and correlation coefficients*

Source of variation	Degrees of freedom	Sum of squares	Mean square	Regression equation	Correlation coefficient	Degrees of freedom
General regression	1	143.97	143.97	$Y=13.37-.0913X$	−0.560**	339
Between tree regressions	22	23.18	1.053*			
Between tree means	22	125.32	5.696**	$Y=14.39-.1557X$	−.665**	22
Error (within trees from individual regressions).	295	166.51	.564			
Between tree regressions+error (within trees, from average regression).	317	189.49	.598	$Y=13.13-.0749X$	−.538**	317

*Significant.
**Highly significant.

The tree-mean volumetric shrinkage varies with mean growth rate in a different way than does volumetric shrinkage of blocks within a tree with growth rate. As shown in table 2, the mean square for tree means of volumetric shrinkage is highly significant as compared with error (line 5). These adjusted tree means differ more than would be expected from chance; tree mean values of volumetric shrinkage deviate significantly from the average regression. In other words, the differences in tree-mean values of volumetric shrinkage are not entirely accounted for by the average regression curve.

Tree-mean shrinkage does change to some extent with mean growth rate because the variance of Y was reduced about 44 percent by the regression of Y on X. In this case, the trend is better than that of the other regressions. The equation of the means shows a regression coefficient of -0.1557 as against -0.0913 for general regression and 0.0749 for average within-tree regression. The correlation coefficient for tree means was -0.665 as compared to -0.560 for total correlation and -0.538 for average correlation. This is the opposite of the results obtained in the rings-per-inch vs. specific-gravity analysis (section I), in which the tree-mean correlation was the lowest of the three coefficients. The tree means fit their regression line better than all the blocks fit their average regression within trees.

The coefficients of regression for the individual trees ranged from $+0.0310$ to -0.2570 and the correlation from $+0.184$ to -0.882. All the trees gave negative coeffiicents except one.

Further details on procedure of analysis and interpretation can be made in a manner similar to that given in the preceding section on rings per inch and specific gravity.

III. RINGS PER INCH AND TANGENTIAL SHRINKAGE

An examination of figure 5 reveals a better association between the variables than was shown for the relationships discussed in sections I and II. The higher correlation may be accounted for in part by the method of measurement of the tangential dimension. The dial-gauge caliper measures only a small width and area. In measuring the green block in the tangential direction one central spot was marked to assure remeasurement in the same place after drying. The ring width was not uniform in some blocks. Hence some measurements of

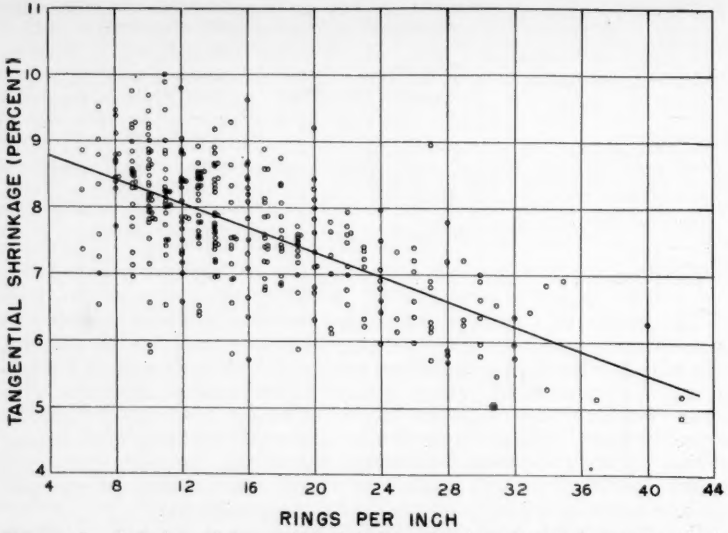

FIGURE 5.—Relation of tangential shrinkage to rings per inch for the blocks from 23 yellow poplar trees.

shrinkage and rings per inch represented values for a narrow-ring zone or for a wide-ring zone. If the measurement is in the center of the zone the effect of ring width should be at a maximum; there should be less counteraction of shrinkage by the adjacent zone of different ring width. It was observed that on the surface of the dried blocks the wide-ring zones were depressed below the level of the narrow-ring zones when these zones alternated in the same block. The difference in level was not always abrupt regardless of the change in ring width. The standard error of estimate of tangential shrinkage for the total regression is ± 0.723 percent.

The statistical data are given in table 3.

TABLE 3.—*Analysis of covariance of rings per inch and tangential shrinkage, together with regression equations and correlation coefficients*

Source of variation	Degrees of freedom	Sum of squares	Mean square	Regression equation	Correlation coefficient	Degrees of freedom
General regression	1	148.44	148.44	$Y=9.15-0.09X$...	-0.676^{**}	337
Between tree regressions	22	11.19	.509			
Between tree means	22	67.53	3.05^{**}	$Y=10.07-.148X$...	$-.713^{**}$	22
Error (within trees from individual regressions)	293	97.84	.334			
Between tree regressions + error (within trees, from average regression)	315	109.03	.346	$Y=8.89-.075X$...	$-.652^{**}$	315

** Highly significant

The range of individual tree regression coefficients was $+0.001$ to -0.198. The range of correlation coefficients was ± 0.009 to 0.921; the average correlation as given in table 3 was -0.652. The tree

regressions or slopes were not significantly different from each other and are, therefore, quite accurately represented by the average regression (third equation, column 5). The correlation between tree means is higher than either the within-tree or the total correlation. This finding is similar to those obtained for rings per inch and volumetric shrinkage.

The data for blocks of 20 rings per inch or more were analyzed separately. The correlation coefficient for this slower growth was −0.66. This indicates about the same correlation for wood of slower growth as for all growth rates (−0.676) on a total correlation basis.

IV. RINGS PER INCH AND RADIAL SHRINKAGE

The correlation of the two variables rings per inch and radial shrinkage was determined on the basis of tree mean values by giving equal weight to each tree, and not on the individual block data. The coefficient obtained as −0.166, a value so small that for the number of trees used it has no significance.

V. SPECIFIC GRAVITY AND VOLUMETRIC SHRINKAGE

The relation between specific gravity and volumetric shrinkage for the blocks is shown in figure 6. The standard error of estimate of volumetric shrinkage is ±0.823 percent. The total correlation coefficient for the statistics shown in figure 6 is −0.734. It follows that about 54 percent of the variance in volumetric shrinkage of the blocks from their mean can be explained by differences in specific gravity. This is considerably better than was found for rings per inch and volumetric shrinkage. Twenty-four trees were used in this part of the study.

A summary of the data obtained is given in table 4.

TABLE 4.—*Analysis of covariance of specific gravity and volumetric shrinkage, together with regression equations and correlation coefficients*

Source of variation	Degrees of freedom	Sum of squares	Mean square	Regression equation	Correlation coefficient	Degrees of freedom
General regression	1	281.21	281.21	$Y=0.941+29.08X$	0.734**	355
Between tree regressions	23	18.76	.82**			
Between tree means	23	97.87	4.26**	$Y=.941+29.08X$	.734**	23
Error (within trees from individual regressions)	309	123.70	.40			
Between tree regressions+error (within trees, from average regression)	332	142.46	.43	$Y=.933+29.09X$	.735**	332

**Highly significant.

The range of individual tree coefficients was 9.00 to 51.66 for regression and 0.372 to 0.961 for correlation. The averages of within-tree values as given in table 4 were 29.09 and 0.735 respectively. These averages, however, are only indicative of the trend of this particular experiment since, as is explained below, they are based on a population that is not homogeneous.

The mean square for the error of estimate of between-tree slopes or regressions is highly significant as compared with error by the F test, indicating that the relation of specific gravity to volumetric shrink-

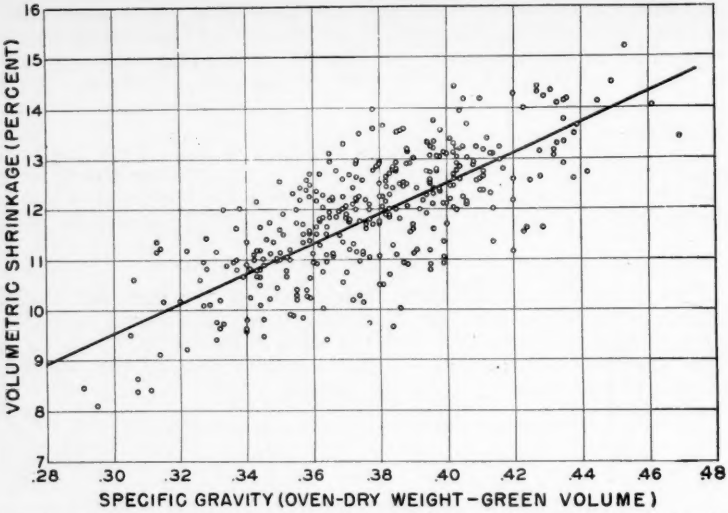

FIGURE 6.—Relation between volumetric shrinkage and specific gravity for the blocks from 24 yellow poplar trees.

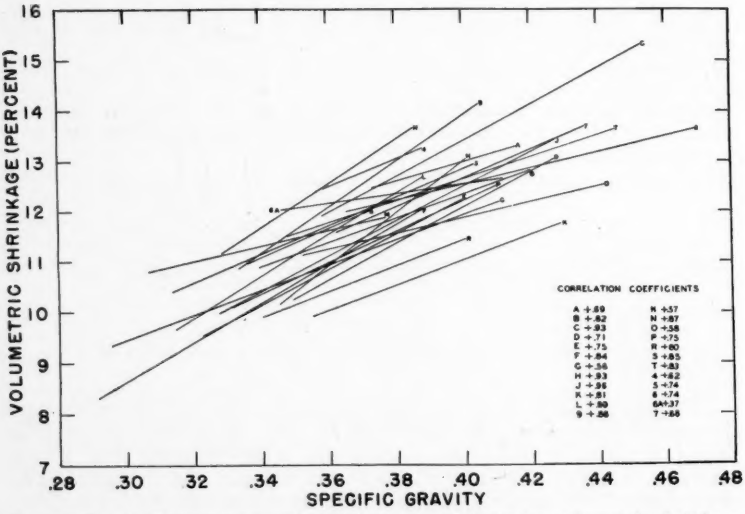

FIGURE 7.—Individual lines and correlation coefficients for volumetric shrinkage and specific gravity of 24 yellow poplar trees.

age is different for the various trees, and the differences in slopes are more than would be expected on the basis of chance from a sample of trees which had curves of common slope. A very significant difference is shown also between the tree regressions, based on their departure from the average within-tree regression. No common slope can fully represent the individual slopes to the extent of accounting for the regression differences from it that would not be due to chance.

The mean square of 4.26 for tree means indicates a highly significant difference between tree means in volumetric shrinkage after adjusting them to an average level of specific gravity. The tree means, therefore, differ more among themselves than would normally be expected from a homogeneous group.

It is interesting to note that the three correlation coefficients in table 4 are practically the same, a feature not found in other analyses.

Figure 7 shows the individual regression lines for specific gravity and volumetric shrinkage. The graph shows the different slopes, the various levels of the slopes, the ranges of the two variables for each tree, and the correlation coefficients for each tree.

In order to check the validity of the use of a straight line for the composite data (fig. 5) as well as to determine the nature of the curves of the individual trees, the data on specific gravity and volumetric shrinkage were plotted for each tree. It was evident from the individual graphs that a straight line properly represented the relation between the two variables in nearly every case and would best express the average relation between all trees.

VI. SPECIFIC GRAVITY AND TANGENTIAL SHRINKAGE

Figure 8 presents graphically the data for relation between specific gravity and tangential shrinkage for all blocks (except near the pith). The regression line shown represents a total correlation coefficient of 0.676. This indicates less association than was found for volumetric shrinkage. The standard error of estimate of Y (tangential shrinkage) for these data is ± 0.727 percent.

A summary of the data is given in table 5.

TABLE 5.—*Analysis of covariance of specific gravity and tangential shrinkage, together with regression equations and correlation coefficients*

Source of variation	Degrees of freedom	Sum of squares	Mean square	Regression equation	Correlation coefficient	Degrees of freedom
General regression	1	148.86	148.86	$Y=0.709+22.18X$	0.676**	334
Between tree regressions	22	9.25	.42*			
Between tree means	22	91.09	4.14**	$Y=.384+19.28X$	.590**	22
Error (within trees from individual regressions)	290	76.42	.26			
Between tree regressions+error (within trees, from average regression)	312	85.67	.27	$Y=1.51+24.31X$	.739**	312

* Significant.
**Highly significant.

The range of individual tree regression coefficients was 10.83 to 39.35; for correlation coefficients the range was 0.218 to 0.937. Applying the F test, it is found that the mean square 0.42 is just at the

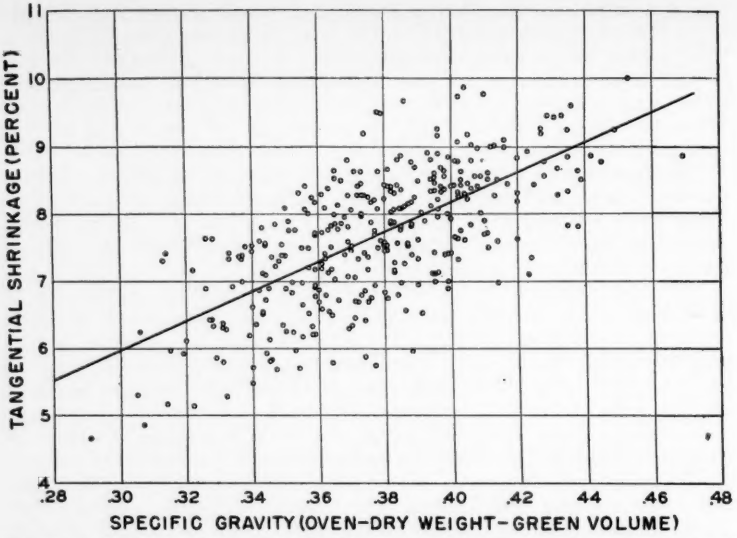

FIGURE 8.—Relation of tangential shrinkage to specific gravity for the blocks of 23 yellow poplar trees.

5-percent level of significance; therefore, the tree regressions differ but little from each other and from their average regression.

The adjusted tree means of tangential shrinkage are highly significantly different from each other. The total variation of tangential shrinkage not accounted for by specific gravity is in part caused by tree-to-tree differences, as is indicated by the fact that the correlation coefficient for tree means (0.590) is lower than the average within-tree correlation (0.739).

VII. SPECIFIC GRAVITY AND RADIAL SHRINKAGE

The association between specific gravity and radial shrinkage was not nearly so good as for the other shrinkages. The summary of data is given in table 6.

TABLE 6.—*Analysis of covariance of specific gravity and radial shrinkage, together with regression equations and correlation coefficients*

Source of variation	Degrees of freedom	Sum of squares	Mean square	Regression equation	Correlation coefficient	Degrees of freedom
General regression	1	25.65	25.645	$Y=0.715+9.261X$	0.487**	330
Between tree regressions	22	6.298	.286**			
Between tree means	22	40.311	1.832**	$Y=.838+8.935X$	.448*	22
Error (within trees from individual regressions)	286	36.083	.126			
Between tree regressions+error (within trees, from average regression)	308	42.379	.137	$Y=.624+9.502X$	.518**	308

*Significant.
**Highly significant.

The standard error of estimate of radial shrinkage in the general regression is +0.500 percent.

The range of coefficients for individual trees was −0.251 to +0.929 for correlation and −3.326 to +22.371 for regression. It is obvious that the association between specific gravity and radial shrinkage is low. The best group relationship was found with the average within-tree regression, where 27 percent of the variance of radial shrinkage was accounted for by variation in specific gravity (r=0.518). Since the tree regressions are not homogeneous, this value is merely indicative of the average for these data.

Differences between the adjusted mean values of radial shrinkage for the individual trees are highly significant. The correlation coefficient for the tree mean values of specific gravity and radial shrinkage (0.448) is between the 5-percent and 1-percent levels of significance. This level of significance coupled with the relatively low correlation gives this relationship only minor practical importance.

VIII. AGE AND SPECIFIC GRAVITY

The association of specific gravity with age as indicated by the number of rings from the pith was determined by grouping the blocks into rings-per-inch classes of 1 to 10, 11 to 20, 21 to 30, 31 to 40, and over 40. The blocks in the first class actually had from 6 to 10 rings per inch. The apparent effect of age was greatest in the 1 to 10 class and decreased to an absence of effect in the slow-growth samples. The curves are shown in figure 9.

The correlation index for the 1–10 class (containing 101 blocks) was 0.62, which accounts for 39 percent of the variance. Included in this class were 27 blocks of 20 years of age or less and when these were excluded from the analysis, the correlation index was 0.45. Considerable scatter existed over the whole range of the curve. Three-fourths of the blocks above 20 years of age were from 9 trees only; only 2 blocks were over 200 years old.

In the 11 to 20 curve there were 211 points representing all trees fairly well, but the deviations were marked. Twenty of the blocks had average ages of 5 to 20 years. The correlation index for this curve was 0.37.

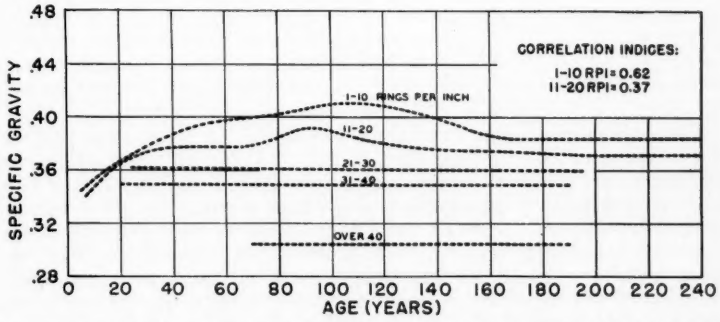

FIGURE 9.—Relation of specific gravity to age of wood. The blocks from 23 yellow poplar trees were grouped into growth-rate classes.

The curve for the 21 to 30 class was based on 53 blocks from 18 trees, the 31 to 40 curve on 12 blocks from 7 trees, and the class over 40 years on 7 blocks from 3 trees.

The wide dispersion of the points about the curves, together with the inadequate number of points and trees represented in some curves, as may be seen from the data given, makes the reliability of these curves questionable. This observation applies especially to the low-age area of the 1 to 10 and the 11 to 20 curves, which show a steep slope and marked deviations, and also to the two bottom curves, for which too few data were available. All the curves as drawn are the best fit of the experimental data. The limits of each curve were determined by the extremes of the points involved. It would be desirable to have this relationship of age and specific gravity checked by additional investigations.

The effect of age was also computed by a different method. The specific gravity for the wood in the outer half of the tree was determined for two classes of trees, one consisting of 17 trees less than 180 years of age at test height, the other of 6 trees more than 180 years of age and averaging about 225 years. The average rings per inch and specific gravity in the younger age class were 19.8 and 0.386, respectively, and for the older class, 17.8 and 0.362. The difference between these specific gravity means was found to be significant by the analysis-of-variance test.

IX. WOOD NEAR THE PITH

As previously stated, blocks averaging less than 2 inches from the pith or those less than 20 years of age were not included in the analysis of data and relationship of properties. The shrinkage and specific gravity values for this wood were computed separately from the wood that lay beyond. The data for each type are given in table 7.

TABLE 7.—*Specific gravity and shrinkage of wood near the pith and of wood away from the pith*

Position and age of wood	Average specific gravity	Average shrinkage			
		Volumetric	Tangential	Radial	Longitudinal
Less than 2 inches from pith and less than 20 years old	0.348	*Percent* 11.71	*Percent* 7.61	*Percent* 3.77	*Percent* 0.17
More than 2 inches from pith and more than 20 years old	.378	11.92	7.67	4.20	.20

The important differences shown in table 7 are in specific gravity and radial and longitudinal shrinkages. Volumetric and tangential shrinkages are about the same for the two groups in spite of the fact that specific gravity was lower for the first group. In other words, these shrinkages of the wood near the pith are greater than would be expected from their normal relation to specific gravity. This was observed also when these data were plotted on the same graph with the data of the wood away from the pith. The points for the wood near the pith were usually in the upper portion or above the other points for a given specific gravity.

To determine the approximate distance from the pith at which the density of the wood became normal, the average specific gravity of the blocks just outside the limits given above was computed. The value obtained was 0.370 which, when compared with 0.378 (table 7), indicates that this wood was about normal. The upper two curves in figure 9 illustrate this point. Examination of the data for the individual trees did not indicate that the lower specific gravity was due to unusually wide rings although these were present in a few cases. The lower specific gravity was found even in wood of the same or a slower rate of growth than that of subsequent years in the same tree. Nor was it true that all trees had the same amount of low-density wood near the pith. In a few cases the wood less than 20 years old and less than 2 inches from the pith was about as dense as the wood subsequently formed. In other cases the wood just beyond this zone was somewhat below normal in density as compared with later wood having approximately the same number of rings per inch. Since the age and distance limits used in this test are the average values for the test piece (usually at the midpoint), no exact limit of age or distance was actually used. However, considering the averages already given and the rings of each tree, it was concluded that for these trees a radius of 2 inches from the pith included practically all the wood near the pith that was subnormal in specific gravity. Variation about this arbitrary limit is to be expected and does exist. Wood with a rate of growth near the pith of 8 to 16 rings per inch (which was the rate for three-fourths of the trees) usually will be 20 years of age or slightly over. These variations are not shown in detail in the curves of figure 9 since it was feasible to show only the average relationship.

X. EFFECT OF CHANGING GROWTH RATE

The range in rate of radial growth was 0.37 inch to 1.5 inches for the first 10 years. The influence of the initial rate of growth at the test height on the specific gravity of the wood subsequently formed was determined by partial correlation of the factors: rings per inch in the first 10 years, average rings per inch, and average specific gravity. The last two factors applied to the wood along the diameter and over 20 rings from the pith.

With the effect of different average rates of growth of the tree eliminated, it was found that the partial correlation coefficient for the rate of growth in the first 10 years and the average specific gravity was -0.157. It was concluded that the growth rate in the first 10 years had no significant influence on the average specific gravity (based on oven-dry weight and volume when green) of the wood subsequently formed or beyond approximately the 20-year-old zone.

Seventeen trees had a period of slow growth (20 or more rings per inch) at some time during their lives, usually about the middle period. In general, the specific gravity dropped to a varying degree in the slow-growth period, and upon the resumption of more rapid or normal growth, it returned to normal or to a value similar to that before the slow growth. This seemed to be true whether the tree had a low, intermediate, or high average specific gravity and irrespective of the rate of growth for the first 10 years, within the range of rate of growth that was found in the experiment.

XI. CROWN-SURFACE RELATIONSHIPS

The area of the crown surface was calculated by the equation for the area of a semiellipse whose semiaxes are a and b, where a and b represent crown depth and average crown radius, respectively. This may not give the exact effective area for a number of reasons, such as irregularity of crown shape, variation in leaf density of the crown, the unknown relation of crown size to photosynthetic activity, etc.; but for want of a better method the above formula was used. The average annual cross-sectional increment in square inches for the last 10 years was computed for each tree, based on the cross section at the end of the first log. These values were correlated with the crown-surface area. The correlation coefficient was 0.60. This exceeds the 1-percent level and therefore is regarded as highly significant. The coefficient of determination indicates that 36 percent of the increment variance was due to differences in crown area.

When the average cross-sectional increment for the last 30 years was used, instead of the increment for the last 10 years, the correlation coefficient was 0.55 as against 0.60 for the 10-year period. Average crown diameter and the cross-sectional increment for the last 10 years gave a correlation coefficient of 0.57. Crown length and area increment gave a coefficient of 0.54. Multiple correlation for the three factors—cross-sectional increment, crown diameter, and crown length—gave a coefficient of 0.59, which is almost the same as that obtained for increment and the crown area, based on the formula of a semiellipse. This is another way of showing that crown diameter and crown length augment each other to only a small degree in accounting for differences in growth increment. If the product of crown diameter and crown length for each tree is plotted against the cross-sectional increment, a correlation coefficient of 0.59 is obtained, which is the same as that obtained in multiple correlation and approximates the coefficient of 0.60 for crown-surface area and cross-sectional increment. The small differences between the coefficients derived from crown area, multiple correlation, the product of crown diameter and crown length, and crown diameter indicate that, for most purposes, crown diameter is to be preferred to crown area as a measure of area of growth increment because fewer measurements and computations are involved.

No adjustment was made in the foregoing data for variation in bole length. An attempt was made to correct for this by computing the approximate bole surface (inside bark, including the height to base of crown) of each tree and the annual radial increment for the last 10 years. This volume increment correlated with crown-surface area gave a coefficient of 0.22. When volume increment was correlated with crown diameter the coefficient was 0.42. Why these correlations for volume increment should be lower than those for cross-sectional increment is not apparent. Possibly the trees with larger crowns put much of the growth increment on the branches and upper bole as well as on the bole below the live branches, or perhaps the volume increment figures are too inaccurate to give entirely dependable results, since the growth rate at various heights and the taper of the tree were not measured on each tree.

There was no significant correlation when rings per inch for the last 10 years were plotted against crown-surface area. There did not appear to be a definite relation between the crown size and the specific gravity of the wood in the outer half of the tree growth, even when the variation in sizes of the tree trunks was taken into account.

XII. PARTIAL CORRELATION ANALYSIS

The coefficients of partial correlation were computed for the variables rings per inch, specific gravity, and volumetric shrinkage. Volumetric shrinkage was used as the dependent variable, or the property upon which the influence of one factor was to be measured while the effect of a third factor or property was eliminated.

The correlation between volumetric shrinkage and specific gravity when rings per inch was held constant was 0.641. The drop from 0.734 for gross correlation to 0.641 for partial correlation indicates that as the rate of growth varies, it has some effect on the true correlation of specific gravity with volumetric shrinkage.

The partial coefficient of correlation between volumetric shrinkage and rings per inch with the influence of specific gravity eliminated was −0.338. The gross coefficient of determination was 0.314 and the partial coefficient 0.114. This relatively large decrease means that the gross correlation of volumetric shrinkage with rate of growth was largely a relationship between specific gravity and volumetric shrinkage, expressing itself, in part, as a rate-of-growth influence.

When the aggregate relationship of these three variables was calculated, it was found that the coefficient of multiple correlation was 0.77, or slightly higher than the original gross correlation between specific gravity and volumetric shrinkage. That the value is not higher is due to the small effect of rings per inch on the shrinkage, as shown above. The multiple correlation indicates that the factors of rings per inch and specific gravity together account for about 55 percent of the variance of the volumetric shrinkage.

XIII. SPECIFIC GRAVITY OF WOOD FROM NORTH AND SOUTH SIDES OF TREE

The average specific gravity of the wood from the north and south sides of each tree was obtained from the data on the blocks on each side, sapwood and heartwood included (except the zone 2 inches from the pith). Equal weight was given for each tree in computing the averages for all trees, since the desired result is concerned with the situation among trees even though they are not of the same size. The average number of rings per inch for each side was approximately the same (17 and 18). The average specific gravity for the north sides was 0.375 and for the south sides 0.377. The two values are not significantly different. In 11 trees the wood on the north side had the higher specific gravity, and in 12 trees, the wood on the south side had the higher specific gravity. The range of ratios of the higher specific gravity to the lower was 1.01 to 1.12 when wood from the north side had a higher specific gravity than wood from the south side, and 1.01 to 1.09 when the reverse was true. The mean in both cases was 1.04.

The average specific gravity of a particular side seemed to be associated with the length of the radius (north or south) of the trees.

In 11 trees the side which had the higher specific gravity was the side of shorter radius, and in 5 trees the side of higher specific gravity was the side of longer radius. In the remaining 7 trees, there was either no appreciable difference in specific gravity between the two sides (less than 2 percent) or else the two radii were nearly the same. Of 8 trees in which one radius was 20 percent greater than the other, 5 had the longer radius on the north side and 3 on the south side. Four of the 8 were heavier on the shorter side, 2 were lighter on the shorter side, and 2 showed no appreciable difference in specific gravity.

XIV. LONGITUDINAL SHRINKAGE

The average longitudinal shrinkage for all the blocks from all the trees (except wood near the pith) was 0.20 percent. The average shrinkage for the wood on the north side of the trees was 0.21 percent and for that on the south side 0.18 percent. The maximum average shrinkage found along a radius in any tree was 0.36 percent. In 14 trees the average longitudinal shrinkage was greater on the side of the lower specific gravity. In only 1 tree was there higher longitudinal shrinkage on the side of higher specific gravity. In the remaining 8 trees the shrinkage was about the same on both sides, or else the specific gravities were nearly the same. The relative length of the north and south radii on each tree also seemed to be associated more or less with longitudinal shrinkage. In 15 trees, the side of longer radius had the greater longitudinal shrinkage, but the ratios for 5 of these were small. In 7 trees the side of shorter radius had the greater longitudinal shrinkage, but in only 3 of these was the relation definite. These results agree with those recorded in section XIII in which it was shown that in 11 trees the side of shorter radius had the higher specific gravity, in 5 the reverse was true, and in 7 either the specific gravity ratio or the radius ratio was so small that the data were neutral. High or low longitudinal shrinkage did not seem to be associated with fast or slow growth or with deviation from the normal in other respects. Since the shrinkage values are not unusual, associated factors may not be present.

The above results are not considered conclusive but are presented as an observed trend which should be checked by other work.

When longitudinal shrinkage was plotted against specific gravity, using the average values of north and south sides, no significant correlation resulted. This comparison presents a different picture from that obtained by comparing ratios of the two sides of a tree. Trees may have a similar north-to-south ratio but be very different in specific gravity in whole or in part.

DISCUSSION

One of the principal reasons for making the statistical analyses presented herein was to determine the reliability and the closeness of association between the various factors that affect specific gravity and shrinkage in wood. It has been common practice to say that certain factors influence specific gravity and shrinkage and either to ignore or to give inadequate evaluation to the usefulness and reliability of the relationship of these factors. For example, there is

general agreement in the literature that the rate of growth has an influence upon specific gravity; but there is very little information to show how much of the variation in specific gravity is due to or is associated with number of rings per inch. A procedure such as the one used in this experiment gives a measure of this association and also provides information on the significance of some factors that contribute to variation.

Only one tree used in this study had an average growth rate as fast as 8 annual rings per inch. This was a codominant which grew at the bottom of the slope near a creek. In the first 10 years this tree grew at the rate of 6 rings per inch; thereafter the rate was uniformly 8 rings per inch. The tree was 21.4 inches diameter breast high and 85 years old. The trees that made the next most rapid growth averaged, respectively, 10.5 and 13 rings per inch.

It is somewhat disturbing to find that so few of the relationships show a high degree of association of the variables involved. In these cases undetermined factors may be of major importance. This seems to be true with respect to rings per inch and specific gravity, for example. It is desirable, at this point, to emphasize the difference between one tree and another in the closeness of association of any two of the variables to be measured. It is evident from the wide range of the coefficients given for the different pairs of variables and from the significance of the mean squares that the relation of, say, specific gravity and volumetric shrinkage is very different from one tree to another and may be very different also from the average coefficient for the group of trees. The differences between these values show also that one cannot rely on a small number of trees for obtaining the measure of a variable factor upon a property of wood that will have sufficient reliability to give the results real worth. This is true also in measuring any single factor or property. In using an equation or a curve to derive one value when the other is known, the derived value represents the average that would be expected from a large number of samples having the same value as the X variable. However, if the best curve that can be made reduces the total variance of Y by only a small amount, say 25 percent or less, we must accept this fact and recognize the limitations of the equation (or curve) as a means of computing or predicting the values that we wish to use as actual values. In this connection the standard error of estimate of the dependent variable, Y, is of some use in indicating the probable limits of error of the estimated value.

Linear relationships have been used for most of the analyses reported in this study. Judging from the data, there seemed to be good reason for doing so; also, the use of linear relationships makes possible the analysis of covariance to evaluate the various factors reported. It is doubtful whether there are sufficient points in the range of less than 10 rings per inch to determine accurately the end of the curve that involves rate of growth. It may be that the curve should flatten out or even drop a little, as is indicated by certain workers (*2*, *6*). In the present study it seems unlikely that the error of the curve, if any, would be more than the change of the ordinate value to the left of 8 rings per inch. The regressions have not been computed to pass through the zero points of the X and Y axes. Rather, the graphs

and statistical conclusions are based on the experimental data without holding to control points. The statistical values obtained should therefore be the best values for the data.

In order to hold to a minimum such variables as climate and soil, the sampling in this study was limited to one area. No positive statement is therefore justified in regard to the results that might have been obtained if trees from other areas had been included. Nevertheless, on the basis of the generally accepted evidence that there may be as much variation in the specific gravity of trees within one large area as between those from widely separated areas, the results of this study should give a fairly good idea of what might have been found had other areas been represented.

As previously mentioned, the test blocks were not taken from the same height in all trees, but the maximum difference of 10 feet in height probably had little influence on the results since butt wood was not used.

Since this project was started other work has been reported which has some relevance to this paper. Stern (*7*), in his report on the strength properties of yellow poplar, reports only a 2 percent greater average specific gravity of sapwood over heartwood and −5 percent for heartwood near the pith.

Luxford and Wood (*2*) found no significant difference in specific gravity between sound heartwood and sapwood. The above results are in good agreement with the facts revealed in this study, in which the specific gravity of the sapwood was 2.4 percent higher than that of the normal heartwood and the specific gravity of the wood near the pith was 7.7 percent lower than the normal heartwood.

In view of the fact that the difference between heartwood and sapwood was small and not highly significant, and taking into consideration the results of other workers, it is concluded that there is no important difference in specific gravity between the heartwood not near the pith and the sapwood of yellow poplar. The evidence indicates, however, that heartwood near the pith has a significantly lower specific gravity than heartwood away from the pith. The average specific gravity of 0.378 (based on volume when green and weight when oven-dry) was about the same as that reported by Stern (*7*) in the one tree used in his project, but was below the average reported by Paul and Norton (*6*) for second growth (0.392) and for young trees in old-growth stands (0.399). Actually, it was between these values and their value for old-growth trees (0.363). As they point out, their value of 0.392 includes the wood near the pith in trees originating in fairly open stands. If that were excluded the average specific gravity would be somewhat higher. The average specific gravity reported by Luxford and Wood (*2*), in a recent study involving 250 random specimens for specific gravity (86 of which were from West Virginia) was 0.38, on the basis of weight when oven-dry and volume when green; the average number of rings per inch was 18. The species average given by Markwardt and Wilson (*3*) is also 0.38; the average number of rings per inch was 14. The specific gravity of 0.378 reported in this paper was from blocks averaging 16 rings per inch.

The evidence presenting an average specific gravity of 0.38 for yellow poplar seems to be well substantiated. If the samples show a high

ratio of either very fast or very slow rate of growth a different average figure may be expected.

Table 8 presents a comparison of the shrinkage values of yellow poplar reported from several sources.

TABLE 8.—*Shrinkage values of yellow poplar*

Reference	Trees	Rings per inch	Specific gravity [1]	Shrinkage			
				Volumetric	Tangential	Radial	Longitudinal
	Number			*Percent*	*Percent*	*Percent*	*Percent*
Present report	23	16	0.378	11.9	7.7	4.2	0.20
Markwardt and Wilson (*3*)	11	14	.38	12.3	7.1	4.0	
Boomsliter (*1*)	1	14	[2].43		7.2	4.1	.15

[1] Based on green volume and oven-dry weight.
[2] Calculated from reported density of oven-dry material.

The differences among the various shrinkages are not large or important with the possible exception of tangential shrinkage. The method of measurement, as pointed out earlier, may account for the higher values obtained in this work.

SUMMARY

Some of the physical properties of yellow poplar (age 86 to 273 years) and some of the factors that might influence these properties were studied. Statistical analyses were used to evaluate these relationships and to indicate the interacting factors.

The specific gravity was found to vary inversely with the number of rings per inch but the correlation coefficient was small (−0.483). The difference between tree regressions and the difference between means of specific gravity of trees were found to be highly significant.

An inverse relationship was obtained between number of rings per inch and shrinkage—volumetric, tangential, or radial.

The variation between tree regressions for rings per inch and volumetric shrinkage and also between tree means of volumetric shrinkage were significantly different. The gross correlation was −0.560.

The total correlation for rings per inch and tangential shrinkage was 0.676. The tree means of tangential shrinkage were significantly different from each other.

The correlation of the tree mean values of rings per inch and radial shrinkage was small and nonsignificant (−0.166).

Volumetric shrinkage increased as specific gravity increased. The total correlation coefficient and the correlation coefficient between tree means were 0.734; thus, specific gravity accounted for 54 percent of the variance of volumetric shrinkage. The regressions for the individual trees and the mean values of volumetric shrinkage between trees varied more between themselves than would be expected from a uniform population.

The gross correlation for specific gravity and tangential shrinkage was 0.676. The tree regressions were significantly different from each other, and the tree means were also significantly different.

The gross correlation of specific gravity with radial shrinkage was 0.487, somewhat lower than with tangential shrinkage. Highly significant differences were found between individual tree regressions and also between tree means of radial shrinkage.

The total correlation was not usually the same as either the correlation of tree means or the average correlation within the trees.

Age was found to have some effect on specific gravity, especially in the blocks of 20 rings per inch or less. However, these results are not considered conclusive.

Wood near the pith was lower in specific gravity, radial shrinkage, and longitudinal shrinkage than wood farther out; in volumetric shrinkage there was little difference.

When the rate of growth changed in a tree there was usually an accompanying change in specific gravity, although the amount of change in specific gravity was quite variable. When the tree resumed its former rate of growth, specific gravity tended to return to its former value.

The initial rate of growth did not appear to influence the average specific gravity of the wood subsequently formed.

Crown-surface area correlated with the annual cross-sectional increment for the last 10 years gave a coefficient of 0.60. The correlation coefficient obtained where crown diameter was used instead of crown surface area was 0.572; with crown length the coefficient was 0.535. With calculated volume increment of the bole and crown-surface area, the correlation coefficient was 0.22.

No difference with respect to specific gravity was found between the north and south sides of the tree. There was some evidence that the side of shorter radius was more likely to have a higher average specific gravity than the opposite side.

The average shrinkage values, excluding wood near the pith, were: Volumetric 11.92 percent, tangential 7.67 percent, radial 4.20 percent, and longitudinal 0.20 percent. The average rate of growth was 16 rings per inch.

The average longitudinal shrinkage was generally greater in wood from the side of the lower specific gravity whether the wood was from the north or the south side of the tree. Likewise, wood from the side of longer radius usually showed a greater average longitudinal shrinkage than wood from the side of shorter radius.

The average specific gravity (based on oven-dry weight and volume when green) of 0.378, obtained in this study, is in good agreement with results obtained by other workers on yellow poplar.

Except in wood near the pith, no important difference was found between the specific gravity of sapwood and heartwood.

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DECAY RESISTANCE OF SEVEN NATIVE OAKS[1]

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INTRODUCTION

Oak is first among the United States hardwoods both in the volume available and in the volume used. This large acceptance is not entirely a result of the quantity at hand. Certain oak species have always been desired for their superior decay resistance and have been widely used for boat construction, ties, piling, bridge timbers and planking, rural-line poles, and other items commonly subjected to considerable decay hazard.

Oak species favored for decay resistance are generally specified commercially as "white oak" and are not otherwise distinguished. The other species are generally referred to simply as "red oak." This broad classification, which for the most part follows the botanical segregation of the species into white oak and red oak (or sometimes black oak) groups, has been convenient and apparently reasonably satisfactory. However, although it has been well established by general experience that the species of the red oak group usually do not last as long as those of the white oak group, there is little specific information to indicate how much inferior they may be in that respect. Moreover, there is practically no information about the relative decay resistance of the respective species within the two groups. Differences in decay resistance also occur within the same species of oak. One has but to observe the differences in service life of posts of a given species in the same fence line to be convinced of this. The more that is known about these differences in resistance both between and within species, the better will be the basis for selecting oak wood to meet varied durability requirements. Insofar as a choice can be made, it is often as inappropriate and as expensive to use wood of high durability on a dry site as it is to place nondurable wood on a

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[2] The study was proposed and its broad features were outlined by Carl Hartley, of the Division of Forest Pathology. The writers are indebted to J. R. Hansbrough, P. V. Mook, E. R. Roth, R. U. Swingle, and A. F. Verrall, of the same division, and to B. H. Paul, of the U. S. Forest Service, for identifying and collecting the test material in the different regions. Much credit is also due R. L. Krause, formerly of the Division of Forest Pathology, for help in conducting the tests.

damp site. In addition to selecting the most appropriate wood at hand to meet different service needs, the time may come when it will also be practicable to grow oak wood of superior decay resistance.

The purpose of the study reported herein was to ascertain by means of laboratory tests what differences in decay resistance exist (1) among some species of the commercially important oaks, (2) among trees of the same species in the same and different localities and regions, and (3) in different parts of the same tree. Samples were obtained from 407 trees. Of 375 trees that constituted the main basis of the study, 222 represented 4 species in the white oak group and 153 represented 3 species in the red oak group. The trees were distributed in 9 different regions in which most of the commercial oak is grown and in 2 or more rather widely separated localities in each region.

In appraising the information presented it should be kept in mind that laboratory decay tests introduce a factor of artificiality that precludes application of the results to quantitative predictions of service life. Nevertheless such tests can be made to indicate with considerable reliability whether one wood is likely to last longer than another in the same situation and whether the difference is likely to be large or small. Also, they are particularly well suited to disclose rapidly trends of association between decay resistance and other measurable characters of the wood.

MATERIALS AND METHODS

SOURCE AND KINDS OF TEST TREES

The seven species of oak tested follow:

White oak group:
- White oak (*Quercus alba* L.).
- Oregon white oak (*Q. garryana* Doug. ex Hook.).
- Chestnut oak (*Q. montana* Willd.).
- Swamp chestnut oak (*Q. prinus* L.; syn., *Q. michauxii* Nutt.).

Red oak group:
- Northern red oak (*Q. borealis* Michx.).
- Scarlet oak (*Q. coccinea* Muench.).
- Black oak (*Q. velutina* Lam.).

The location of the trees in the nine different regions that were considered is shown in figure 1.

To minimize any variation in decay resistance that might be caused by differences in tree size, dominants and codominants within a range of diameters at breast height (d. b. h.) from 15 to 18 inches were used exclusively in all phases of the study except the phase dealing specifically with the relation of decay resistance to tree size. With a few exceptions six to eight trees of a species were sampled in each locality.

In addition to the trees selected in localities shown in figure 1, 32 white oak trees having a wide range of diameters were sampled in a locality near Madison, Wis.; these furnished all the information that was gathered relative to decay resistance and tree size.

TEST SPECIMENS

The test samples were removed from the trees in the form of increment-borer cores, 0.21 inch in diameter, and as small blocks. The cores were relied upon for evidence of differences in decay resistance among trees and among localities and regions and were taken from all

FIGURE 1.—General regions in which the test oak trees were located: C, Central; MR, upper Mississippi River Valley; NA, northern Appalachian; NE, northeast coast; P, Pacific coast; PP, southeast Piedmont Plateau; S, southern; SA, southern Appalachian; SE, southeast coast. The numerals following the region symbols designate the well-separated localities.

trees. The blocks were used for determinations of trends of decay resistance in different parts of individual trees and were taken from only 17 of the trees.

Cores were used in most of the tests because they could be rapidly obtained from a large number of standing trees without serious injury to them. Although only about one-tenth the size of the blocks, they appeared from correlation and variance analyses to give as reliable results if they were weighed more accurately. Six cores were taken from each tree at breast height, three from one side and three from the side directly opposite. The sapwood was eliminated and the outermost 2 inches of heartwood was tested. The sapwood was identified or its identity confirmed in all cases by means of a colorimetric pH test, as described in Forest Products Laboratory Technical Note 253 (*10*).[3]

The blocks, 1 by 1 by ¼ inch in size with the short axis parallel with the grain, were obtained from felled trees. They were sawed out consecutively across an entire diameter located at two different heights in the trunk, one at breast height and the other near the upper limit of the merchantable part of the trunk.

Most of the specimens were collected in February or March, when the trees were dormant in all localities except Louisiana and Texas. In the specimens from these States there was no evidence that the postdormant condition was a material factor of the decay resistance. Samples were taken only from trees having characteristic fruit and bark as described for the species. The identity of the samples of

[3] Italic numbers in parentheses refer to Literature Cited, p. 152.

black oak was confirmed by observing the bark in the laboratory under ultraviolet light. The inner bark typically fluoresces with a blood-red color not observed in the other species.

TESTING PROCEDURE

Decay resistance was ascertained by exposing the cores and blocks to pure cultures of selected decay fungi. This was done in 6-ounce glass bottles of the French-square type, each containing 25 ml. of malt-agar nutrient medium.[4] The fungus was first allowed to cover the surface of the medium. A sterile V-shaped glass rod, 4 mm. in diameter, was then laid on the center of the fungus mat; this served as the support for the single test specimen introduced directly afterward into each bottle. Before the specimens were tested, they were given a partial sterilization treatment by steaming them while air-dry in glass bottles for 20 minutes at 212° F. Such treatment of air-dry wood probably affects its decay resistance very little. The test units were incubated for 4 months at 80°.

The extent of decay was measured by the percentage loss in dry weight of wood. Both before and after they were tested, the specimens were dried to constant weight in equilibrium with a relative humidity of 30 percent and a temperature of 80° F. The percentage losses in weight were determined on the basis of these weights, thus giving a result essentially on an oven-dry basis but with the advantage that no risk of altering the decay resistance by actual oven drying was entailed.

Initially, three different decay fungi were used in considering all variables except diameter. These were *Poria monticola* Murr. (Madison 698),[5] a very destructive species causing brown rot and perhaps one of the most prevalent fungi attacking pine, Douglas-fir, and oak boat timbers (*4*); *Lenzites trabea* Fr. (Madison 617), a brown rotter that attacks a variety of woods; and *Stereum frustulosum* Fr. (R. P. 56461–R), which produces a white pocket rot in dead oak timber and logs and which was the only white rot fungus frequently isolated from boat timbers.

Two cores from opposite sides of each tree and two blocks from each position sampled in the felled trees were tested against each fungus, thus making a total of six independent measures of decay resistance per tree or position in a tree.

The relation of white oak decay resistance to d. b. h. was ascertained about 3 years after the other phases of the study had been completed. By that time it had become apparent in supplementary observations that, although brown rot fungi are common in the decay of oak posts, ties, and structural wood, white rot fungi are probably fully as important generally. For example, in 34 black oak fence posts near Madison, Wis., about 20 percent of the heartwood decays were mixed brown and white rots, 24 percent were brown rots, and 56 percent white rots. In a study of decay of oak ties and posts Roth (*6*) found that 3 of the 6 fungi responsible for most of the decay resulting from infections subsequent to felling of the trees were white rotters. Con-

[4] Consisting of 2.5 percent of Trommer's diastasic malt extract and 1.5 percent of agar in distilled water.

[5] This fungus was originally called *Poria microspora* Overh. It was received from Ross W. Davidson, Division of Forest Pathology, as Wash. 106.

sequently, in the consideration of the d. b. h. variable only *Poria monticola* and *Stereum frustulosum* were retained of the original 3 fungi and with these was used *Polyporus versicolor* Fr. (Wash. 72074, or Madison 697), one of the most destructive, widespread, and versatile of the white rot fungi attacking hardwoods.

In order to determine whether the conclusions derived from use of the original three fungi would also be applicable to decay by strictly white rot fungi,[6] a repeat test was made on wood blocks (p. 130) For this purpose *Poria monticola*[7] and *Polyporus versicolor* were used again, with two additional white rotters—an unidentified species (Madison 4411–1) that had been isolated from decayed gum wood in an Army glider and Madison 517,[8] a species of uncertain classification that had been widely used over a long period for testing the toxicity of wood preservatives.

RESULTS

RELATIVE DECAY RESISTANCE OF THE TESTED OAK SPECIES

The relative resistance of the tested oak species to decay by the three fungi used in the initial testing is indicated in figure 2. Species having the largest percentage weight loss had, of course, the lowest resistance. The order of differences in resistance between the white oak and red oak groups is in line with general service experience. The differences in resistance shown for the four species of the white oak group were not anticipated, however, and it is apparent from these differences that species in the white oak group are by no means in a single class of decay resistance. Insofar as these results may be generally representative, white oak (*Quercus alba*) would appear to occupy a more or less intermediate position of resistance in the white oak group. On the average the chestnut oak was substantially more resistant than the white oak, and the swamp chestnut oak was considerably less resistant. The Oregon white oak, although represented by very few trees, appears to be at least as resistant to decay as the white oak.

The species of the red oak group (black, northern red, and scarlet) lost on the average about four times as much weight by decay as did the chestnut oak and more than twice as much as the white oak. Differences found among the three species of the red oak group were slight and of doubtful practical significance.

Although the foregoing general observations, which were based on the average results given by all three test fungi, are probably representative of differences among the species to be expected commonly, it should be noted that the differences in resistance among the species

[6] Inasmuch as *Stereum frustulosum* produces a white pocket rot, it cannot be considered as a white rot fungus in the strictest sense. Moreover, it has been reported as failing to give the typical white-rotter reaction on gallic or tannic acid medium (*3*).

[7] Although *Poria monticola* had been used in the first tests, there was no certainty that some changes in the decay resistance of the wood might not have taken place during the subsequent 3-year period. Actually, the results obtained with this fungus in the first and the repeat test were substantially alike (correlation coefficient=0.88).

[8] This fungus has been listed in previous reports from this laboratory as *Fomes annosus* (Fr.) Cke., but now it has been found by several investigators to be culturally more like *Polyporus tulipiferus* (Schw.) Overh.

in the white oak group to the individual fungi were not altogether similar. The relative resistance of the respective species to the brown rot fungus *Poria monticola* was much like that indicated by the average results. On the other hand, the differences in resistance to the second brown rot fungus, *Lenzites trabea*, although the most marked of all between the red and the white oak group, were small and of doubtful significance among the species of the white oak group. Findings in other tests similarly have indicated *L. trabea* to be capable of attacking rather strongly hardwoods of moderate to low resistance but only weakly those of greater resistance. The white pocket rot fungus

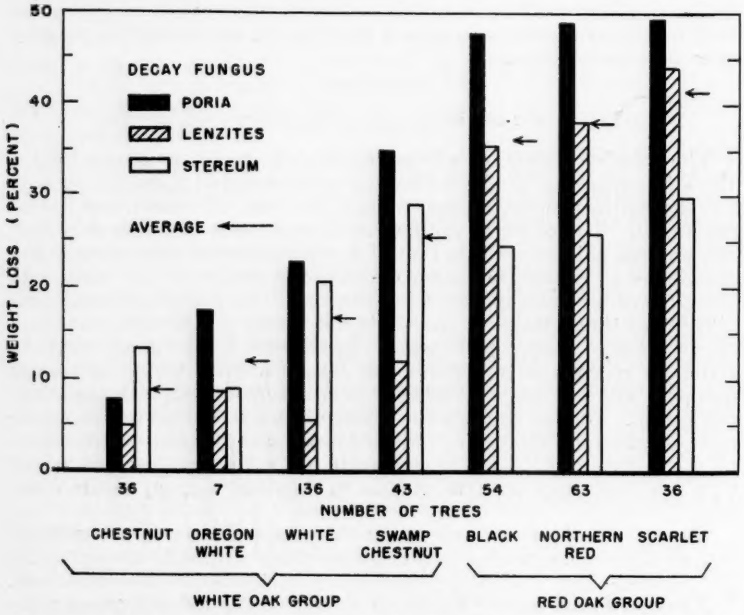

FIGURE 2.—Average weight loss caused by decay in cores from trees of the different oak species. Species with largest percentage of weight loss had least decay resistance.

Stereum frustulosum, which is a specialized inhabitant of oak wood, decayed the species of the white oak group almost as rapidly on the whole as *P. monticola;* this indicated comparable differences in resistance among those species. *S. frustulosum* decayed the red oak species more slowly than either of the other two fungi, however, with the result that the difference in resistance to it between the red and the white oak group was smaller; only the chestnut and Oregon white oaks demonstrated resistance to *S. frustulosum* substantially superior to that of the red oak group.

The tests on wood from different positions in the tree, described on page 148, furnish limited additional data on the resistance of the chestnut, white, swamp chestnut, and northern red oaks, in this case to

the three typical white rot fungi, *Polyporus versicolor*, Madison 517, and Madison 4411–1. The species differences in weight loss caused by these fungi were on the average smaller than those caused by the other fungi, mainly because of a slower general attack by Madison 517 and Madison 4411–1 and the fact that, although *P. versicolor* decayed the white oak species more rapidly than any of the other fungi, the differences in resistance to this fungus were not correspondingly larger. Of greater significance, however, is the fact that the relative resistance to the three fungi exhibited by the outer heartwood (representing the major volume of heartwood) of the species was indicated to be very much like that denoted by the average weight losses shown in figure 2. The remainder of the heartwood was characterized by a reversal in the order of resistance between the northern red and the swamp chestnut oak and between the white and the chestnut oak.

VARIABILITY IN DECAY RESISTANCE AMONG TREES OF THE SAME SPECIES

Some further light is shed on the species differences by observing the variability in decay resistance among the trees of the respective species as shown in figure 3. This figure is based on smoothed cumulative-frequency curves of the weight loss. Essentially, each species diagram is a double frequency histogram having unequal class intervals. The asymmetry of a number of the diagrams undoubtedly can be

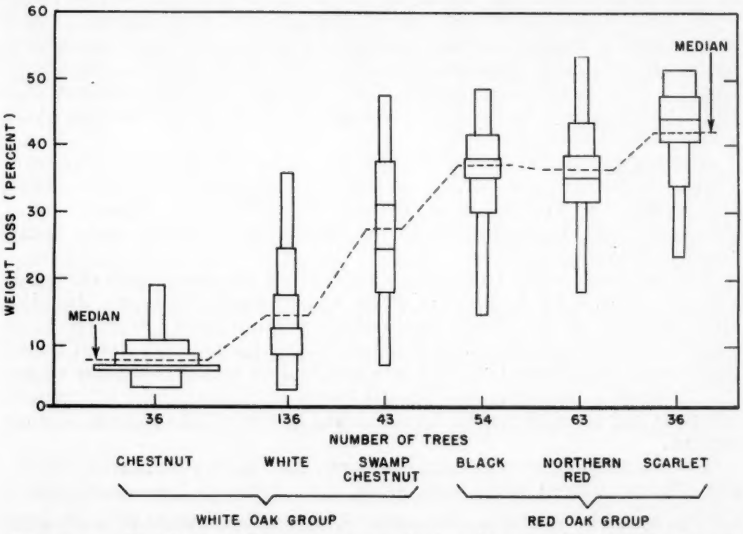

FIGURE 3.—Distribution diagrams for weight loss by trees in the different oak species, based on averages for *Lenzites trabea*, *Poria monticola*, and *Stereum frustulosum*. All diagrams have the same total area, representing 100 percent of the trees of the different species, and each of the 5 segments in a diagram has the same area (20 percent of the total) and represents 20 percent of the trees as arranged in order of weight loss. Thus the percentage of trees of a given species falling within a particular weight-loss range can be estimated from the percentage area occupied by the corresponding portion of the species diagram.

ascribed partly to the comparatively small number of trees sampled. It is also evident, however, that some of the "bunching" of trees, which was most marked with chestnut and scarlet oaks, is a reflection of the restrictions on weight loss imposed by zero and the upper limits of weight loss. The upper limit for brown rot fungi, as indicated in previous tests by the writers and in tests by Findlay (*5*), appears to be near 60 to 65 percent.

Perhaps the most striking information brought out by figure 3 is the fact that the variability in resistance among trees of a particular species may be comparatively large.[9] Consequently, although the average resistance of one species may differ substantially from that of another, a considerable proportion of the trees of the two species may have wood in the same resistance class. For example, although the wood of the black oak trees lost on the average more than twice as much weight as that of the white oak (*Quercus alba*) trees, about 50 percent of the white oak trees and about 40 percent of the black oak fell within the same range of weight losses (15 to 35 percent). This evidence in itself might well account for conspicuous differences in the service life of oak wood of the same species. Moreover, it reveals the possibility of growing oak wood of greatly improved decay resistance by propagating strains of superior resistance. If vegetative propagation of oak ultimately becomes practicable or if seedling progenies inherit a sufficient portion of parental resistance, strains of white oak or swamp chestnut oak might be selected, for example, with two or even three times the average decay resistance of those species. Not only would a higher average resistance thus be provided, but also a more uniform and therefore a more predictable service life would result. The weight-loss distribution diagram for the chestnut oak (fig. 3) would seem to be a conservative illustration of what might be accomplished along this line.

Another possibility would be selection of red oak species with heartwood resistance equal to that of the average white oak, which, with the capacity of the red oaks to take preservative treatment, would give ties and structural timbers combining strength and decay resistance to a high degree.

Not only resistance to decay in service but also resistance of standing trees to heart rot might be improved by such selection. Judging from the findings in a recent study of the wood of black locust (*Robinia pseudoacacia* L.),[10] the decay resistance may be as characteristic and permanent a feature of a given strain of timber as anything else about it. Stands of oak once established reproduce more often by sprouts after cutting than from seed, thus tending to perpetuate the established strains.

No clear difference was found between the decay resistance of white oak (*Quercus alba*) wood and wood from trees of the same species

[9] The ranges of weight loss illustrated in figure 3 are somewhat larger than those representative of the actual variation in decay resistance. That is because the weight losses also include the experimental error of determining them. Increases from this source, however, are probably no larger than, if as large as, the increases that would be had purely as a result of increasing the sampling basis.

[10] SCHEFFER, T. C., and HOPP, H. THE DECAY RESISTANCE OF BLACK LOCUST HEARTWOOD. (Unpublished manuscript.)

sometimes referred to in the Northeast as "yellow-bark oak." Likewise, no difference was found between northern red oak wood and so-called "gray oak" wood of this same species.

LOCALITY AND REGIONAL DIFFERENCES IN DECAY RESISTANCE OF THE TESTED OAK SPECIES

The over-all variability just observed in the decay resistance among trees of a given oak species does not appear to consist simply of more or less uniform differences among the trees everywhere. Rather it appears to be partially contributed by differences in average levels of resistance of wood from the different localities and regions. Many such differences were very marked. For example, in table 1 it may be noted that the average weight loss produced by *Poria monticola* in white oak wood from locality 1 of the upper Mississippi River Valley region was 36.3 percent, whereas that in wood from locality 3 of the same region was only 5.9 percent. Similarly, the average weight loss caused by *P. monticola* in white oak from this region as a whole was 19.4 percent, whereas that in wood from the northeast coast was 31.9 percent. Smaller but nevertheless considerable differences appear in the corresponding averages for decay by the other two fungi.

Two questions raised by these findings are (1) whether such locality and regional differences might be purely a random result, the main features of which would not necessarily be obtained if other sets of trees were sampled on the same areas and (2) whether these differences if they are real are of genetic origin or are attributable to differences in conditions under which the trees were grown. A general answer to the first question may be had by treating the data statistically according to the method of analysis of variance. Terminal computations needed for this analysis are given in table 2.

If the differences in weight loss between cores from opposite sides of the trees (section D) are taken as the nearest measure of experimental error, it is apparent from the number of significantly larger variances of section C (denoted by significant F values) that there were real differences in decay resistance among white oak trees even in the same locality. Inasmuch as the trees in any one locality were of approximately the same size and age and were grown in practically the same general environment, this may be construed as an indication of genetic differences in resistance. A similar and rather general variation in resistance among trees within localities is indicated in the other species considered in table 2; it was not so pronounced as with the white oak, however, and was statistically significant for considerably fewer of the regions individually.

In the same way the variation in resistance among trees within localities can be used to test the variation in average resistance of wood from the different localities of a region (section B). Twelve of the twenty-seven locality variances for individual regions in section B were significantly larger than the corresponding tree variances in section C; thus they were larger than might reasonably be attributed to random differences among the sampled trees. Although the number of localities considered in each region was too small to permit appraisal

TABLE 1.—*Average weight loss caused by decay in wood from various oak species, regions, and localities*

Region and locality from which test samples were obtained	Decay caused by *Poria monticola* in—							Decay caused by *Lenzites trabea* in—						
	White oak	Oregon white oak	Chestnut oak	Swamp chestnut oak	Northern red oak	Black oak	Scarlet oak	White oak	Oregon white oak	Chestnut oak	Swamp chestnut oak	Northern red oak	Black oak	Scarlet oak
Upper Mississippi River Valley (MR):	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	36.3				45.0	38.2		6.4				33.7	30.6	
2	15.9				48.0	45.0		3.7				34.2	36.4	
3	5.9				48.5	40.0		4.0				25.9	19.8	
Average	19.4				47.2	41.1		4.7				31.3	29.0	
Central (C):														
1	23.4							7.0						
2	18.3							3.9						
3	20.2							4.4						
4	11.0							4.1						
Average	17.2							4.7						
Northeast coast (NE):														
1	12.2				54.4	55.7	46.3	5.7				45.6	42.9	34.6
2	35.6				51.7	52.7	44.2	7.1				37.5	39.6	46.3
3	44.6				54.3			10.4				53.7		
4			14.8							4.5				
Average	31.9		14.8		53.5	54.2	45.3	7.9		4.5		46.0	41.2	40.5
Northern Appalachian (NA):														
1	39.1				44.1			7.1				31.4		
2			7.9							4.1				
3			4.3							4.4				
Average	39.1		6.1		44.1			7.1		4.3		31.4		
Southern Appalachian (SA):														
1	23.9							7.2						
2	29.7		8.5		42.3	50.5	53.5	4.5		6.3		38.6	35.8	53.1
3	21.2							4.6						
4	15.9		6.2		52.6	48.5	56.5	4.3		5.2		36.3	39.9	42.3
5						54.0	53.2						43.0	52.8
Average	22.3		7.4		47.4	51.0	54.4	4.6		5.7		37.5	39.6	49.4

Southeast Piedmont Plateau (PP):														
1	----	----	4.2	----	----	45.0	43.3	----	----	5.0	----	----	33.1	30.7
2	----	----	----	----	48.3	----	----	----	----	----	----	42.9	----	----
Average	----	----	4.2	----	48.3	45.0	43.3	----	----	5.0	----	42.9	33.1	30.7
Southeast coast (SE):														
1	----	----	----	19.8	----	----	----	----	----	----	6.2	----	----	----
2	----	----	----	41.7	----	----	----	----	----	----	17.1	----	----	----
3	----	----	----	43.8	----	----	----	----	----	----	12.9	----	----	----
4	14.7	----	----	26.8	----	----	----	4.6	----	----	8.0	----	----	----
Average	14.7	----	----	33.0	----	----	----	4.6	----	----	11.1	----	----	----
Southern (S):														
1	17.0	----	----	42.4	----	----	----	7.6	----	----	17.0	----	----	----
2	31.3	----	----	51.2	----	----	----	5.5	----	----	25.8	----	----	----
Average	19.9	----	----	43.7	----	----	----	7.2	----	----	18.2	----	----	----
Pacific coast (P):														
1	----	19.9	----	----	----	----	----	----	8.9	----	----	----	----	----
2	----	11.1	----	----	----	----	----	----	8.7	----	----	----	----	----
Average	----	17.4	----	----	----	----	----	----	8.8	----	----	----	----	----
Species average	22.7	17.4	7.7	34.8	49.1	47.7	49.5	5.6	8.8	4.9	12.2	38.5	35.7	44.3

TABLE 1.—*Average weight loss caused by decay in wood from various oak species, regions, and localities*—Continued

Region and locality from which test samples were obtained	Decay caused by *Stereum frustulosum* in—							Average decay caused by all fungi in—						
	White oak	Oregon white oak	Chestnut oak	Swamp chestnut oak	Northern red oak	Black oak	Scarlet oak	White oak	Oregon white oak	Chestnut oak	Swamp chestnut oak	Northern red oak	Black oak	Scarlet oak
Upper Mississippi River Valley (MR):	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	24.7				31.1	17.6		22.5				36.6	28.8	
2	14.6				21.3	23.3		11.4				34.5	34.9	
3	9.1				16.2	13.8		6.3				30.2	24.5	
Average	16.2				22.9	18.2		13.4				33.8	29.4	
Central (C):														
1	20.9							17.1						
2	22.7							15.0						
3	20.0							14.9						
4	20.6							11.9						
Average	21.0							14.3						
Northeast coast (NE):														
1	18.1				32.2	26.2	17.9	12.0				44.1	41.6	32.9
2	23.2				19.4	28.0	31.9	22.0				36.2	40.1	40.8
3	27.7				29.6			27.6				45.9		
4			11.8							10.4				
Average	23.4		11.8		27.0	27.1	24.9	21.1		10.4		42.2	40.8	36.9
Northern Appalachian (NA):														
1	22.0				25.0			22.7				33.5		
2			20.8							10.9				
3			11.4							6.7				
Average	22.0		16.1		25.0			22.7		8.8		33.5		
Southern Appalachian (SA):														
1	33.6							21.6						
2	22.9		8.5		25.8	18.8	28.9	19.0		7.8		35.6	35.0	45.2
3	23.5							16.4						
4	20.7		15.3		27.4	30.4	32.2	13.6		8.9		38.8	39.6	43.7
5						33.8	34.4						43.6	46.8
Average	22.8		11.9		26.6	27.7	31.8	16.6		8.3		37.2	39.4	45.2

Southeast Piedmont Plateau (PP):														
1			12.6			31.5	34.9			7.3			36.5	36.3
2					32.1							41.1		
Average			12.6		32.1	31.5	34.9			7.3		41.1	36.5	36.3
Southeast coast (SE):														
1				20.6							15.5			
2				30.6							29.8			
3				33.1							29.9			
4	16.4			28.4				11.9			21.1			
Average	16.4			28.2				11.9			24.1			
Southern (S):														
1	20.2			32.7				14.9			30.7			
2	25.2			34.8				20.7			37.3			
Average	21.2			33.0				16.1			31.6			
Pacific coast (P):														
1		9.3							12.7					
2		8.7							9.5					
Average		9.1							11.8					
Species average	20.7	9.1	13.4	29.0	26.0	24.8	30.0	16.3	11.8	8.7	25.3	37.9	36.1	41.3

TABLE 2.—*Tree, locality, and regional differences in decay resistance indicated by analysis of variance of the weight losses*

Source of weight-loss variation	White oak decay caused by—						Chestnut oak decay caused by—					
	Poria			*Stereum*			*Poria*			*Stereum*		
	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]
A. Among means of regions	6	1,039.9	1.1	6	161.5	1.1	3	135.7	5.0	3	44.4	0.2
B. Among means of localities within regions:												
All regions	11	959.4	3.1**	11	149.2	3.2**	2	27.0	.6	2	201.9	8.7**
In region MR [2]	2	1,914.0	10.0**	2	498.6	11.3**						
In region C	3	269.0	.7	3	11.2	.2						
In region NE	2	2,404.0	11.9**	2	206.8	5.0*						
In region NA							1	38.9	.9	1	265.1	8.4*
In region SA	3	261.8	.6	3	52.1	1.4	1	15.2	.4	1	138.7	6.5*
In region SE												
In region S	1	324.9	.8	1	41.0	1.7						
C. Among means of trees within localities:												
All localities	118	308.7	5.3**	118	47.0	4.7**	30	48.0	2.0*	30	23.2	1.8*
In region MR	21	191.1	4.4**	21	44.1	10.5**						
In region C	31	378.7	6.1**	31	66.2	4.2**						
In region NE	23	201.6	2.2*	23	41.5	4.6**	5	133.6	3.4	5	17.0	1.2
In region NA	7	216.8	3.1	7	47.9	3.2	10	42.9	3.6*	10	31.5	2.3
In region SA	21	441.4	10.9**	21	37.3	3.8**	10	34.0	.8	10	21.3	1.2
In region PP							5	.4	.3	5	16.8	8.4*
In region SE	7	292.9	10.1**	7	41.9	6.5**						
In region S	8	400.4	10.5**	8	24.7	4.8*						
D. Between cores from opposite sides of trees:												
All trees	129	58.0		134	9.9		36	24.2		36	13.0	
In region MR	20	43.8		24	4.2							
In region C	33	62.1		33	15.6							
In region NE	26	92.9		26	9.0		6	39.7		6	14.0	
In region NA	8	69.1		8	15.1		12	11.8		12	13.8	
In region SA	24	40.3		25	9.9		12	40.2		12	17.2	
In region PP							6	1.2		6	2.0	
In region SE	8	29.1		8	6.4							
In region S	10	38.2		10	5.1							

Red oak decay caused by—

Source of weight-loss variation	Swamp chestnut oak decay caused by—						Red oak decay caused by—								
	Poria			*Stereum*			*Poria*			*Stereum*			*Lenzites*		
	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]	Degrees of freedom	Variance	Variance ratio (F) [1]
A. Among means of regions	1	667.5	0.7	1	133.8	0.7	4	162.4	2.1	4	104.5	0.4	4	638.6	2.5
B. Among means of localities within regions:															
All regions	4	923.7	2.8*	4	198.3	3.0*	5	78.9	1.7	5	265.3	5.8**	5	252.7	1.5
In region MR [2]							2	21.6	.4	2	349.3	17.3**	2	130.8	.8
In region C															
In region NE							2	17.0	1.0	2	310.5	4.7*	2	492.7	4.9*
In region NA															
In region SA							1	317.2	5.8*	1	6.8	.1	1	16.6	.1
In region SE	3	1,209.7	3.4*	3	263.2	4.1*									
In region S	1	65.6	.5	1	3.8	.0									
C. Among means of trees within localities:															
All localities	37	325.6	4.9**	37	65.7	9.7**	53	46.7	1.4	53	45.8	2.1**	53	167.8	2.3**
In region MR							15	48.0	1.2	15	20.2	.9	15	156.0	3.1*
In region C															
In region NE							18	16.4	1.1	18	66.1	3.3**	18	99.7	2.1
In region NA							5	160.4	7.1*	5	28.1	1.6	5	249.6	2.8
In region SA							10	54.9	.8	10	52.9	1.8	10	253.8	2.0
In region PP							5	23.4	.6	5	53.1	2.5	5	194.6	1.8
In region SE	32	354.1	5.0**	32	64.0	8.9**									
In region S	5	142.6	3.4	5	76.6	16.6**									
D. Between cores from opposite sides of trees:															
All trees	42	66.1		43	6.8		61	33.8		63	22.0		63	74.2	
In region MR							16	39.8		18	21.6		18	49.5	
In region C															
In region NE							21	14.2		21	20.2		21	48.5	
In region NA							6	22.6		6	17.1		6	89.7	
In region SA							12	64.5		12	28.6		12	128.7	
In region PP							6	36.2		6	20.9		6	110.4	
In region SE	35	71.0		36	7.2										
In region S	7	41.5		7	4.6										

*Statistically significant difference at the 5-percent level.
**Statistically significant difference at the 1-percent level.
[1] Obtained by dividing the variance by the corresponding variance below it in the table. For example, variances in group A are tested by the corresponding variances in group B, those in group B by corresponding ones in group C, etc.
[2] Region symbols explained in legend for figure 1.

of the situation in general, this result suggests that to a limited extent at least there tends to be a closer genetic relation among trees of a given oak species in the same locality than there is among the trees of different localities. This inference is valid, of course, only if environmental or other extraneous factors had no prominent influence on the results.

Regional differences in the average decay resistance of a particular species of oak (section A) are indicated by the variance ratios to have been in no case larger than might be expected among localities of comparable size in a single region. It may be noted in this connection that for testing the regional differences the pooled variances of section B, representing the average among-localities variances for all regions, were used. In spite of the marked differences in magnitude among some of the variances that were pooled there was no evidence in tests of variance homogeneity (*9*) that any of these differences were sufficiently large to preclude pooling. It may be further noted that even when tested by the individual corresponding variances of smallest magnitude in section B, only two of the nine regional variances (section A) were indicated to be statistically significant.

Three practical conclusions from table 2 and the foregoing variance analysis are suggested:

(1) Oak trees of the same species and approximate size from the same wood lot or locality commonly will have marked differences in decay resistance.

(2) Wood of the same oak species from one locality often averages consistently higher or lower in decay resistance than that from another locality in the same region.

(3) Oak wood from one region as a whole is not likely to be appreciably more resistant than wood of the same species from another region; occasional impressions to the contrary are probably gained from wood taken from comparatively limited areas, such as localities, and thus not adequately representing whole regions.

Regarding the question whether these tree and locality differences are of genetic origin, no reliable evidence could be found of a relation between the decay resistance of individual trees in a locality and differences in their immediate environment or in their most recent growth characteristics as measured by ring counts in the outer heartwood and the sapwood, respectively, and by the width of the sapwood. However, a slight relation between ring count and width of sapwood and locality differences in average decay resistance was indicated. Among localities the resistance tended to be less as the growth rings in the outer heartwood and in the sapwood were narrower and as the sapwood was narrower. By far the best evidence of this was shown by *Poria monticola* decay in the white oak, but the correlation coefficients characterizing the relation among localities of weight loss to ring width in the outer heartwood and the sapwood and to sapwood thickness in this species were only -0.47, -0.56, and -0.58, respectively, (based on 18, 17, and 17 localities, respectively). At most, therefore, only about one-third of the variance among localities in the resistance of the white oak to decay by *P. monticola* might be explained by differences in any of these growth characters, and much less of the variance in white oak resistance to the other two fungi or of the

variance in resistance among localities of the other oak species could be attributed to differences in these characters.

To check further on the possibility of environment as a factor of locality differences in decay resistance, computations were made of the correlation between locality averages of weight loss for pairs of species that came from the same localities. The assumption was that if environment were an appreciable factor this would be indicated by a tendency for the decay resistance of the different species to vary in similar order from locality to locality. An over-all tendency of this sort is denoted by the correlation coefficients shown in table 3. But here, also, the generally low values of the coefficients (which were individually significant statistically in only one instance) indicate that environmental differences among the localities might explain only a comparatively small part of the differences. From this and the preceding evidence, therefore, it is concluded that at least a large share of the observed differences in resistance within species is probably attributable to strain differences.

TABLE 3.—*Correlation between locality averages of weight loss in different oak species from the same localities* [1]

Species compared	Localities	Correlation coefficient (r)
Northern red oak and—	*Number*	
White oak	9	0.41
Black oak	7	.77*
White oak and—		
Swamp chestnut oak	3	.96
Black oak	7	.24
Scarlet oak	4	.50
Scarlet oak and—		
Chestnut oak	3	.62
Northern red oak	4	−.24
Black oak and—		
Chestnut oak	3	.80
Scarlet oak	6	.02

*Statistically significant at the 5-percent level.
[1] Averages based on weight loss caused by *Poria monticola*, *Lenzites trabea*, and *Stereum frustulosum*. (See table 1.)

RELATION OF DECAY RESISTANCE TO SIZE OF TREE

Decay resistance in relation to size of tree was determined only for white oak on the assumption that any tendencies exhibited would probably apply, in some degree at least, to the other species. Data were obtained on increment-core test samples from 32 trees in a single locality. It is apparent from the plotted results (fig. 4) that there was a rather marked tendency for the decay resistance of the outer heartwood to increase with size of tree. This was true with respect to all three of the test fungi and, as indicated by the correlation coefficients, with nearly equal prominence.

It should be noted that the trees on which this diameter-relation study was made were in an approximately even-aged, closed stand in which some of the trees were suppressed, so that large differences in diameter occurred when age was fairly constant. But if oak follows the same general pattern as has been found for black locust,[11] much the same relation between outer heartwood resistance and d. b. h.

[11] See footnote 10, p. 136.

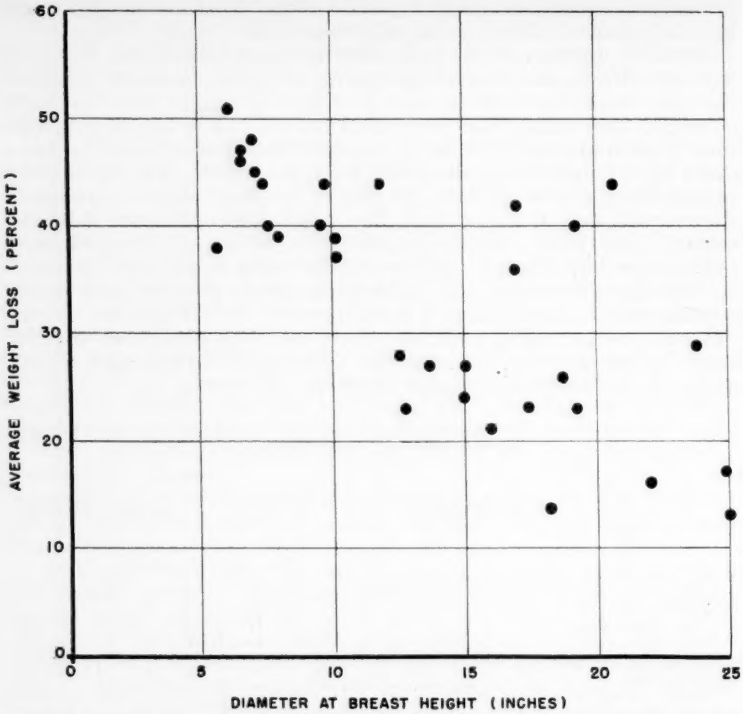

FIGURE 4.—Relation between the diameter of white oak (*Quercus alba*) trees in a single stand and the weight loss caused by decay in wood from the outer heartwood. (Each point represents the average weight loss caused by *Poria monticola*, *Polyporus versicolor*, and *Stereum frustulosum* in the six cores from each tree. The correlation coefficients for d. b. h. and weight loss caused by these fungi individually were −0.72, −0.75, and −0.73, respectively.)

might be expected in open-grown trees of different ages as well as sizes.

VARIABILITY IN DECAY RESISTANCE WITHIN INDIVIDUAL TREES

As stated, ratings of the decay resistance of the respective trees were based on increment cores taken from the lower trunk in the outer 2 inches of heartwood. Such restricted sampling obviously could lead to erroneous conclusions if this part of the trees did not represent reasonably well the entire merchantable part of the trunk. Partly as a check on this point, a number of trees were tested by block samples taken consecutively through the trunk. It also was desired to find out whether there might be large enough differences in decay resistance among various parts of the trunk to warrant consideration when using wood from large trees. The results of this phase of the testing, with the three fungi used first, are summarized in figure 5. The trees sampled for this part of the study, like those sampled for species and tree differences, were in the 15- to 18-inch diameter class; moreover, the individual trees of each species came from different, widely separated localities.

The outer heartwood of all four species represented was more resistant to decay by the three fungi used in determining species and tree differences than was the inner heartwood in both the lower and the top portion of the trunks. Moreover, the change in resistance from the outer to the inner heartwood, although tending to be irregular in individual trees, was on the average progressive. With respect to the major volume of wood in the trunk,[12] these over-all trends did not differ greatly with the different species. The inner, lower-trunk portion of the northern red oaks, which failed to show the same trend, represented considerably less than half the heartwood volume of the trees. Consequently, much the same relative order of decay resistance of the species dealt with (fig. 2) presumably would have been indicated had the heartwood been sampled more completely.

In the larger logs, as indicated by the lower-trunk curves of figure 5, the differences in decay resistance between the inner and the outer heartwood clearly were as great as the differences between some of the oak species. Markedly superior durability is not to be expected

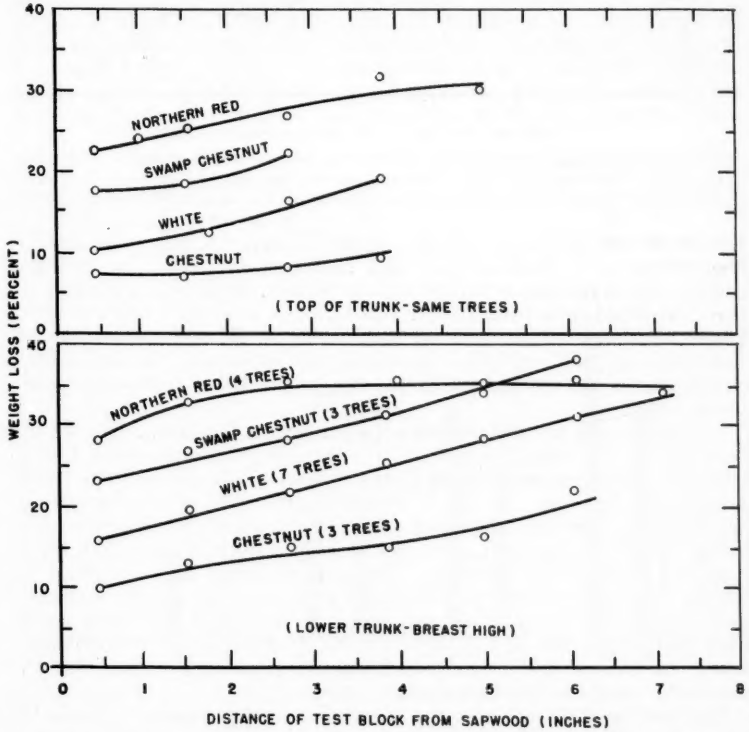

FIGURE 5.—Weight loss in blocks from different parts of individual oak trees. (Based on averages for the indicated number of trees and decay caused by *Poria monticola*, *Lenzites trabea*, and *Stereum frustulosum*.)

[12] The outer half of the heartwood radius represents approximately three-fourths of the total heartwood volume.

in the central heartwood of large logs, even of the more decay-resistant white oaks. Similar radial decreases in decay resistance from the outer to the inner heartwood have been reported for a number of species other than oak (*1*, *2*, *7*, *8*).[13]

It should be kept in mind that this variability in decay resistance within individual trees also may be more representative for some fungi than for others. Only slight or no radial trends were found in the average weight loss caused by the three white rot fungi, *Polyporus versicolor*, Madison 517, and Madison 4411–1 (fig. 6). In white oak

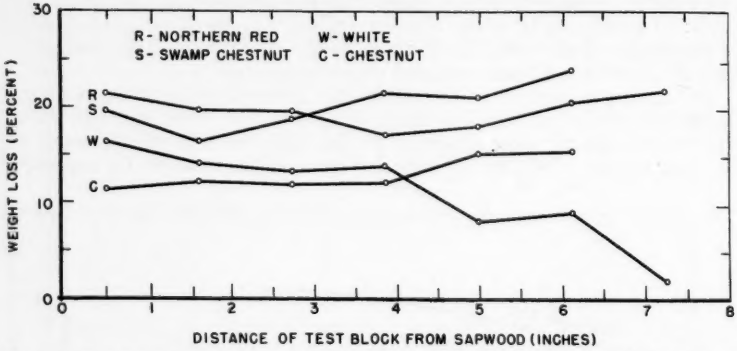

FIGURE 6.—Average weight losses caused by three white rot fungi, *Polyporus versicolor*, Madison 517, and Madison 4411–1, in oak blocks from the basal portion of the same trees and the same radial positions as represented in figure 5.

the trend was the reverse of that shown in figure 5, reflecting mainly the influence of Madison 517 and Madison 4411–1. The average radial trend of resistance to *Polyporus versicolor*, the most destructive of the three fungi, was from higher resistance in the outer heartwood to lower resistance in the central heartwood in all the species except northern red oak, in which no trend was apparent. No consistent radial trends were apparent in the upper trunks in tests made with these fungi.

In considering the differences between figures 5 and 6, it should be recalled (pp. 133 and 134) that the wood was 3 years older when tested with the fungi represented in figure 6 than when tested with those represented in figure 5. It is possible, therefore, that changes in the fungus-inhibiting properties of the wood, which would make the radial trends in the two cases not strictly comparable, might have occurred during this interval. The only evidence on this point is had in the results obtained with *Poria monticola*, which was included in both series of tests. That the radial differences in resistance to at least this fungus had not changed markedly is indicated by the correlation coefficient (0.88) characterizing the relation between the *P. monticola* results in the two cases.

Figures 5 and 6 were also the basis of the supplementary estimate of species differences in resistance to white rot fungi (p. 133).

Rather marked differences in decay resistance vertically in the trunk also are revealed in figure 5. Taken at equal distances from the sapwood, the heartwood of the upper trunks was more resistant

[13] See footnote 10, p. 136.

to decay than that of the lower trunks. Inasmuch as this difference occurred in the trees of all four species, it might reasonably be expected rather generally among the oaks. Unlike the radial trends, however, it has not been found in the other woods studied. The most durable heartwood of black locust, western red cedar, European larch, and redwood has been found in the basal portion of the trees (*1, 2, 8*).[14]

Differences between the upper and the lower trunks in resistance to the three typical white rot fungi are indicated by the following average percentage weight losses for the top and bottom logs, respectively: Chestnut oak, 9.7 and 12.3; white oak, 12.3 and 14.2; swamp chestnut oak, 22.0 and 19.3; northern red oak, 12.4 and 20.5. Only for the swamp chestnut oak was the difference contrary to the results shown in figure 5.

The sapwood of all domestic species has generally been considered to have comparatively little resistance to decay. The present findings for oak are quite in line with this belief; however, some sapwood differences paralleled the differences in heartwood. In the tests represented by figure 7 the sapwood from the upper part of the trunk was indicated to be slightly more resistant than that from the lower trunks in three of the species; also, the sapwood of the white oaks was more resistant than that of the red oak. Among the species of the white oak group, the resistance of the sapwood followed the same order as that of the heartwood except in the case of chestnut oak. It is interesting to observe here that the white oak (*Quercus alba*)

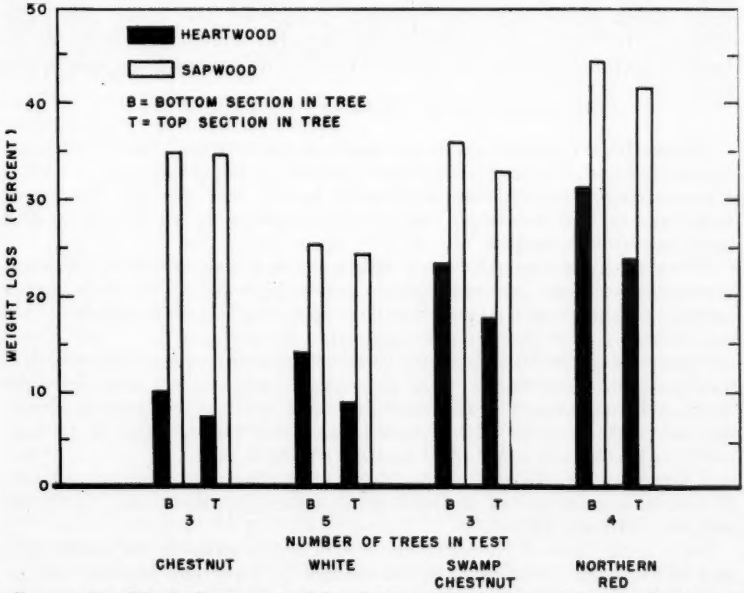

FIGURE 7.—Weight losses caused by decay in blocks from the outer heartwood and in adjacent sapwood blocks. (Losses are averages for the indicated number of trees and for decay caused by *Poria monticola, Lenzites trabea,* and *Stereum frustulosum.*)

[14] See footnote 10, p. 136.

sapwood had about the same resistance as the red oak heartwood. However, little practical significance can be attached to the sapwood differences inasmuch as the level of resistance exhibited in all cases was comparatively low.

DECAY RESISTANCE AND THE SPECIFIC GRAVITY OF OAK WOOD

The relation of decay resistance to the specific gravity of the wood was not a specific subject of this study. Nevertheless, certain conclusions regarding it may be drawn from data already presented. First, it was found that the resistance of the outer heartwood of white oak trees tended to decrease as the width of growth rings narrowed. Such a relation among trees of the same general diameter has already been noted (p. 144), with a correlation coefficient of -0.47 for weight loss and width of rings in the heartwood. For trees of different sizes, represented in figure 4, the relation between percentage weight loss (caused by *Polyporus versicolor*) and ring width was characterized by a coefficient of -0.50. This evidence suggests that inasmuch as the specific gravity of hardwoods, especially the ring-porous species, also tends within limits to decrease as the ring width becomes narrower, the wood of lower specific gravity would decay somewhat more rapidly. However, the radial trends of decay resistance (figs. 5 and 6) give evidence contrary to this. Toward the center of the trees the specific gravity was progressively higher as a result of the more rapid growth when the trees were young, whereas the decay resistance was progressively lower or for much of the wood more or less uniform. It thus seems likely that the specific gravity of oak wood has little effect on its decay resistance, being largely overshadowed by other factors such as the location of the wood in the tree and the size of the tree.

SUMMARY AND GENERAL CONCLUSIONS

Laboratory decay tests were made on heartwood from 222 trees representing 4 commercial species in the white oak group and 153 trees representing 3 commercial species in the red oak group. The trees were located in 9 important oak-growing regions and in well-separated localities in each region.

Wood of the white oak group on the average was substantially more resistant to decay than that of the red oak group. This is in agreement with the general experience that species of the red oak group are not suited to uses involving considerable decay hazard.

Species of the white oak group were not uniformly resistant to decay, however, and some commercial distinction among them as to durability may be warranted. The most resistant of these species was chestnut oak; next in order of decreasing resistance were Oregon white oak, white oak (*Quercus alba*), and swamp chestnut oak.

There was no evidence of practical differences in resistance among the three species of the red oak group, namely, black oak, northern red oak, and scarlet oak.

Individual trees of the same species, of approximately the same size, and in the same locality differed markedly from one another in resistance. This was true of all four species examined, but especially so of white and swamp chestnut oaks. Practically and mathematically significant differences in average resistance also occurred among localities in the same region. Although considerable differences were also found among regions as a whole, they were generally no greater than

among localities within regions. The results thus indicate that it may be possible to obtain especially resistant oak wood by going to selected localities, but they do not support the belief that the oak wood of some entire regions is much superior in decay resistance to wood of the same species in other regions. Furthermore it is apparent that the use of white oak provides assurance of superior decay resistance in general but that some individual trees of this species and most of the trees in certain localities may have only moderate resistance.

This variability in resistance among trees appeared to be attributable more to genetic differences than to differences in the environment of the trees. The possibility presents itself, therefore, of selecting and propagating oak trees with wood having not only a longer but also a more uniform service-life expectancy.

The outer heartwood of white oak (*Quercus alba*) trees in the approximately even-aged stand studied for this relation was higher in decay resistance as the d. b. h. of the trees was larger.

In three species of the white oak group and in northern red oak the resistance to decay by two brown rot fungi and a white pocket rot fungus was progressively lower from the outermost heartwood to the pith. This trend occurred in both the basal and the upper portion of the trunks. Radial differences in resistance to decay by three other fungi, all white rotters, were generally smaller, and in white oak an opposite trend was indicated by two of the fungi. The differences with respect to the first three test fungi were large enough to account for very considerable differences in the service life of wood from different parts of large logs. In fact, some of the central heartwood of the white oak trees was no more resistant than that of northern red oak wood. This finding might be considered further justification for the common discrimination against boxed hearts (log centers) for such purposes as boat timbers.

In the same four species the heartwood in the upper trunks was, with one exception, more resistant to all the fungi than that in the lower trunks. In the swamp chestnut oak this difference was exhibited in resistance to the two brown rot fungi and the white pocket rot fungus, but not in resistance to the three typical white rotters. Heartwood of the top log might be expected, therefore, to remain serviceable as long as wood from other parts of an oak tree and probably substantially longer than central heartwood from the larger, basal log.

There was some association between the decay resistance of the sapwood and that of the heartwood. The sapwood of all species in which it was tested decayed comparatively rapidly, however, confirming the general experience that sapwood by and large is not durable.

From indirect comparisons, the specific gravity of the wood appeared to be no more than a minor factor in its decay resistance. Similarly, the rate of growth appears to have little possibility as a criterion of resistance.

The variability in decay resistance with locality, tree size, and position of the wood in the tree, as well as the uncorrelated differences among trees, indicates that comparisons of species for decay resistance may be unreliable unless many trees from numerous localities covering the range of the respective species are sampled and unless the trees are of approximately the same size (or of the sizes most

utilized) and the samples are taken from about the same place in each tree. It was indicated in the present study that if differences in the resistance of the outer heartwood also are suitably representative of differences in the resistance of the interior heartwood, as with the oaks, increment-borer cores from the outer 2 inches of heartwood provide satisfactory test specimens; their use makes it practicable to include many trees in the sample with minimum expense.

Cores must be taken at a uniform height; if all cores could be taken 8 or 10 feet from the ground, they would represent the tree as a whole somewhat better than if taken 4½ feet from the ground as was done in the present study. The procedure of taking two cores from opposite sides of each tree for each test fungus worked well. If five or six fungi were employed, a single core from each tree for each fungus would be good sampling, although it would fail to provide a base for testing the significance of differences among individual trees. The use of several fungi is advisable, and for any broadleaved tree species at least one white rot fungus such as *Polyporus versicolor* should be included among the test fungi. Of the brown rot fungi *Poria monticola* is excellent for general use.

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CHEMICAL REMOVAL OF ENCRUSTANTS FROM DEW-RETTED HEMP FIBER[1]

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INTRODUCTION

The bast fibers of dew-retted hemp (*Cannabis sativa* L.) are at a disadvantage for textile use because of the presence of encrusting materials. These encrustants, which make up roughly 30 percent of the retted hemp fiber, consist largely of lignin, pentosans, pectic substances, protein, and ash (*5*).[3] They serve as a binding material which holds the fiber bundles together and add strength, but they are rather loosely held and in time and with handling of the fiber they partially slough off. As a result of the great variation in these encrusting substances, physical testing of bast fibers is very difficult. Therefore it is believed that a more uniform basis which would permit a better comparison of fibers should be found. Most chemical degumming treatments are partly effective for removing the encrustants, but some of them cause rather great degradation of the primary constituent of the fiber, cellulose. Reagents which degrade the cellulose chain would, of course, be of little value for this kind of treatment.

Alcohols have been used in pulping wood, which is essentially getting down to the cellulose. Aronovsky and Gortner (*1*) found that alcohols with at least four carbon atoms of which at least three are in a straight chain are best suited for pulping. Organic alcohols if effective in removal of encrustants because of their solvent action should also cause the least cellulose degradation and are worthy of a thorough trial as degumming agents.

In order to ascertain what chemical treatments would remove encrustants from dew-retted hemp fiber and their effects on the fiber, the tests reported herein were made.

MATERIAL AND METHODS

Dew-retted hemp fiber considered to be of about average length was used in the tests. It was air-dried and cut in about 2-inch lengths before treatment with a degumming reagent. Each sample was

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[3] Italic numbers in parentheses refer to Literature Cited, p. 159.

refluxed for an experimental period in a large test tube with a cold finger for condensing vapors. After refluxing was complete, the degumming reagent was washed off, usually with water only; if the reagent was practically insoluble in water, however, a preliminary washing was given with ethanol to facilitate the removal. The fibers were then pressed between paper towels and dried.

Part of most samples were subsequently treated by boiling 1 hour in 1-percent sodium hydroxide and then ½ hour in 4-percent boric acid. The boric acid was used to free the fiber of sodium hydroxide, which interfered with the nitration and determination of the degree of polymerization. Since the latter concerns the cellulose chain, most of the determinations were made on samples from which the encrustants had been removed.

The nitration method used was essentially that of Berl (*2*) except that the nitration was carried out at 10° C. rather than at room temperature. Cellulose nitrate was dissolved in butyl acetate to make a 0.25-percent solution. This was accomplished by revolving between two parallel bars a small glass jar containing the mixture and steel bearings. After solution the cellulose nitrate was filtered through a coarse-fritted glass crucible. The viscometer used was that of Cannon and Fenske (*3*), the viscosity being determined at 25°±0.02° with the time of flow 100 seconds or more.

Calculations from degree of polymerization were based on the following formula of Coppick (*4*):

$$[\eta]=\frac{\ln \eta r}{c}\ (1+0.5c)$$

where

$[\eta]$=intrinsic viscosity
$\ln$=natural log
ηr=relative viscosity
c=concentration in grams per 100 ml.

The degree of polymerization was calculated from Kraemer's formula (*6*):

$$\text{Degree of polymerization}=K[\eta]$$

where

$$K=270.$$

Degree of polymerization, which is affected by various factors, indicates how well fibers withstand treatment to remove encrustants. A low value is evidence of cellulose degradation and therefore of decrease in fiber strength.

Nitrogen in the cellulose nitrate was determined by the Lunge nitrometer.

The percentage nitrogen in the fiber after nitration, which shows the degree of nitration, is dependent on how well the degumming and alkali treatments remove the encrustant from the primary constituent, cellulose.

Breaking strength of the fiber was measured on the Scott tester, model D. H. After loose ends were removed, the sample was cut in 25-cm. lengths and conditioned at 65±1 percent relative humidity. Spool-type clamps, measuring 7.5 cm. from center to center, were

used. Ten breaking tests were made on each sample, and the average breaking strength was reported in kilograms per gram of fiber.

RESULTS

The role played by encrustants in the physical strength of raw commercial bast fibers was determined by testing duplicate samples of dew-retted hemp fiber with the encrustants intact and with the encrustants removed by boiling 1 hour in 1-percent sodium hydroxide and then ½ hour in 4-percent boric acid. The fiber with encrustants

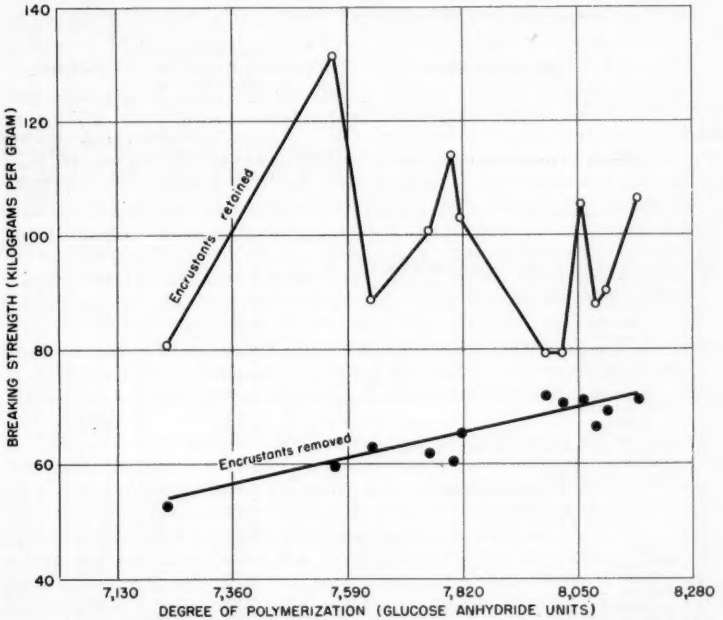

FIGURE 1.—Relation between degree of polymerization and breaking strength of dew-retted hemp fibers with and without encrustants.

removed had a much lower breaking strength than that with the encrustants present (fig. 1). Cellulose in the samples with encrustants averaged 70.3 percent and in those without encrustants 95.7 percent. Breaking strength and degree of polymerization were very closely correlated in the samples without encrustants ($r=0.94$).

The data presented in figure 1 help to answer several questions about the retting process. The over-all variability in strength of fibers with encrustants removed, as measured by degree of polymerization, was relatively slight, a range of approximately 10 percent. The strength of such fibers, like that of most commercial fibers, is essentially that of the primary constituent, cellulose, and depends on length of cellulose chain. Such strength, measured by degree of polymerization, is average strength, which is not affected by weak spots to the

same degree as strength measured by mechanical breaking. The data for fibers with encrustants present substantiate the already known fact that dew retting is irregular and indicate that much of the nonuniformity in quality and strength of such fiber is due to irregularity in encrustant removal.

The results of treating dew-retted hemp fibers with various degumming reagents for different periods (table 1) indicate that they vary in effectiveness and that care in selecting is essential.

TABLE 1.—*Effect of chemical removal of encrustants from dew-retted hemp fiber on degree of polymerization and extent of nitration*

[Alkali boil = boiling 1 hour in 1-percent sodium hydroxide and then ½ hour in 4-percent boric acid]

Sample No.	Degumming reagent		Degree of polymerization in glucose anhydride units		Nitrogen	
	Description [1]	Time of boiling	After degumming treatment	After degumming treatment plus alkali boil	After degumming treatment	After degumming treatment plus alkali boil
		Hours	*Number*	*Number*	*Percent*	*Percent*
1	None		[2] 6,722	[3] 7,790	12.30	12.92
2	Sodium chlorite (1 percent in 3-percent acetic acid at 70° C.)	½	7,767		13.10	
	Sodium carbonate: [4]					
3	1 percent	1	8,117		12.78	
4	3 percent	1	8,110		12.67	
5	5 percent	1	8,119		12.73	
6	10 percent	1	8,326		12.62	
	Sodium sulfite: [4]					
7	1 percent	1	6,813		12.53	
8	3 percent	1	6,548		12.70	
	Sodium borate: [4]					
9	1 percent	1	6,504		12.15	
10	3 percent	1	7,033		12.59	
11	Sodium hydroxide (2 percent in 95-percent ethanol)	1	7,452		12.95	
	Monoethanolamine:					
12	3 percent in 95-percent ethanol	1	7,026	7,158	12.60	13.05
13	2.5 percent in glycerol	1	7,222	7,280	13.05	13.10
14	5 percent in glycerol	1	6,831	6,033	13.04	13.04
15	do	2	6,491	6,258	12.92	13.09
16	Xylene	1	7,383	7,335	12.50	13.15
17	Methanol	1	6,718	7,721	12.56	13.01
18	Ethanol (95 percent)	1	6,722	7,659	12.40	13.17
19	Butanol	1	7,473	7,944	12.56	13.22
20	Isobutanol	1	7,729	7,590	12.53	13.07
21	Amyl alcohol	1	7,061	7,526	12.10	12.80
22	Methanol and butanol (equal parts)	1	7,606	8,096	12.38	12.96
23	Ethanol and butanol (equal parts)	1	7,510	8,211	12.44	13.12
24	Butanol and glycerol (equal parts)	1	7,326	8,211	12.10	13.30
25	Ethanol, butanol, and glycerol (equal parts)	1	6,941	7,832	12.22	13.24
26	Ethylene glycol	1	6,918	6,941	12.75	12.85
27	do	4	7,107	7,015	12.98	12.98
28	Ethylene glycol followed by bleach [5]	4	6,481	6,194	13.07	13.17
29	Ethylene glycol	8	7,107	6,364	12.85	12.80
30	Ethylene glycol followed by bleach [5]	8	6,100	6,318	13.29	13.23
31	Glycerol	1	7,107	7,121	12.48	12.70
32	do	4	5,994	6,539	12.80	12.85
33	Glycerol followed by bleach [5]	4	6,472	5,842	13.12	13.24
34	Glycerol	8	6,334	6,550	12.83	13.06
35	Glycerol followed by bleach [5]	8	5,948	5,771	13.04	13.04

[1] Reagent 100 percent unless indicated otherwise.
[2] Value for original fiber.
[3] Value after alkali boil only.
[4] Treatment with reagent followed by ½-hour boiling in boric acid.
[5] Bleach = ½ hour in sodium chlorite in 3-percent acetic acid at 70° C.

The first 11 samples show the effects of using inorganic alkalies and salts to remove the encrusting materials. Sodium hydroxide was the most effective of the inorganic compounds, excluding the sodium chlorite bleach, in the removal of encrustants as measured by the percentage of nitrogen. Sample 1 before the alkali boil had a lower degree of polymerization because of two factors: (1) greater nitration of pentosans, which would have a tendency to lower the degree of polymerization, and (2) increase of polymerization with increased nitration. Also some degumming reagents may more selectively remove the lower fraction and thus favor a higher degree of polymerization in the treated fiber. Bleaching with sodium chlorite (sample 2) increased nitration and gave a high degree of polymerization, which indicated little break-down of the cellulose chain. Samples 3 to 6, treated with different concentrations of sodium carbonate, showed less removal of encrustants and a higher degree of polymerization, indicating that there was some degradation of the sample treated with sodium hydroxide (sample 1). The concentration of sodium carbonate had little effect on encrustants or the cellulose chain, no doubt because of the high buffer action of this reagent. Treatment with sodium sulfite resulted in increased removal of encrustants as measured by nitration and also greater degradation of cellulose as the concentration of the reagent increased. Furthermore, the sulfite-treated samples showed more cellulose break-down than those treated with sodium hydroxide or sodium carbonate. Sodium borate acted similarly to sodium sulfite, although it was not so effective in the removal of encrustants. The higher degree of polymerization at the 3-percent level was perhaps due to increased nitration. Sodium hydroxide in ethanol resulted in good removal of encrustants and little degradation of cellulose.

The action of monoethanolamine as a delignifier of wood tissue (*7*) has been known for some time, and the same chemical has been used in the determination of cellulose (*8*). Samples 12 through 15 show the effects of using monoethanolamine in ethanol or glycerol. The amine in glycerol has definite advantages over that in ethanol. Monoethanolamine in glycerol was used above its boiling point, and it was therefore more effective. The 2.5-percent concentration did just as well as the 5-percent one in removing the encrustants, and 2 hours had no advantage over 1 hour. Monoethanolamine caused some degradation of cellulose, although not so much as sodium sulfite and sodium borate. Judged by the percentage of nitrogen, the additional removal of encrustants with sodium hydroxide did not cause additional nitration; however, there was greater cellulose degradation in samples 14 and 15 after alkali boil. This greater break-down of cellulose in the higher concentration of monoethanolamine and after the longer boiling time is evidence of better opening up of the fiber bundle for the action of sodium hydroxide.

Samples 16 through 25 show the effects of treatment with xylene or certain alcohols singly and in combination on dew-retted hemp fiber. While xylene is not an alcohol, it acted very much like the alcohols in that it opened up the fibers for more effective action of other reagents such as sodium hydroxide. The degree of polymerization was generally higher when the alcohol was followed by sodium hydroxide. A possible explanation is that there was less extraneous material

connected with the fiber and therefore less low-viscosity material. The higher nitrogen values are evidence of purer cellulose, or better removal of encrustants. A lower nitrogen value for the alcohols used in combination than for those used singly indicates lower removal of encrustants, or a suppressing action by the combination. The combinations of alcohol gave very high degrees of polymerization when followed by the sodium hydroxide boil. A possible explanation may be the better removal of the shorter chained molecules such as pentosan. There has been evidence that some of the pentosan fractions are held much more tenaciously than others by cellulose. The higher alcohols may expose this hard-to-remove fraction to easier removal by other reagents. Cellulose in fiber boiled in four of the alcohols singly—ethanol, butanol, ethylene glycol, and glycerol—averaged 91.5 percent, while in these same samples after boiling for 1 hour in 1-percent sodium hydroxide it averaged 97.4 percent.

Ethylene glycol and glycerol were the two highest boiling alcohols used for encrustant removal. The effects of these two alcohols alone with boiling times of 1 to 8 hours or followed by the sodium hydroxide boil, bleach, or a combination of the two are shown by samples 26 through 35. Ethylene glycol was the most effective of the alcohols in the removal of encrustants during a 1-hour boiling period; however, the lower degree of polymerization indicates greater degradation of cellulose. Glycerol also resulted in cellulose destruction as measured by degree of polymerization. The degradation of the cellulose chain by treatment with glycerol seems to be due to the greater heat rather than to the chemical action, since high temperatures are known to degrade cellulose. Ethylene glycol alone caused no greater degradation in 8 hours than in 1 hour. These two high-boiling alcohols may have some dehydrating action which makes the fibers more subject to oxidation and in general to greater break-down when the alcohol treatment is followed by the sodium hydroxide boil, a bleach, or a combination of the two.

SUMMARY AND CONCLUSIONS

In order to ascertain the effect of degumming dew etted hemp fibers on cellulose degradation, more than 30 treatments were tested with and without subsequent boiling with sodium hydroxide.

The tests showed that the formation of cellulose nitrate and the subsequent determination of degree of polymerization and percentage of nitrogen may be used as an index to encrustant removal and resulting fiber degradation and quality. Sodium hydroxide and sodium carbonate are good chemicals to use in removing encrustants. The former is more effective, but it causes some degradation of the cellulose chain. Increasing the concentration of sodium carbonate over the 1-percent level did not give better removal of encrustants or cause greater break-down of cellulose. A 2.5-percent concentration of monoethanolamine in glycerol gave excellent removal of encrustants, although it caused some cellulose degradation. The lower boiling alcohols such as methanol, ethanol, butanol, isobutanol, and amyl alcohol are not very effective in removing encrustants; however, they do open up the fiber and allow other mild reagents to act more effectively. Of the two high-boiling alcohols (ethylene glycol and glycerol), ethylene glycol was better in removal of encrustants and caused

slightly less degradation of cellulose. The higher boiling alcohols have a tendency to make the fiber more subject to oxidation in bleaching. Increasing the boiling time over 1 hour did not greatly increase the removal of encrustants, but, especially in case of glycerol, it did cause a lowering of the degree of polymerization.

These tests indicate that degumming of bast fibers can be undertaken with a minimum of cellulose degradation and that encrustant removal to a common cellulose base will result in more uniform physical testing.

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